Naval Research Laboratory
Stennis Space Center, MS 39529-5004

NRL/CR/7401--95-0019

An Economic Analysis of Abyssal Seafloor Waste Isolation

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Contract: N00014-94-1-G913

Prepared for

NAVAL RESEARCH LABORATORY

Marine Geosciences Division
Code 7400
Stennis Space Center, MS 39529-5004

January 13, 1995

REPORT DOCUMENTATION PAGE

Form Approved
OBM No. 0704-0188

1. Agency Use Only *(Leave blank).*

2. Report Date.
January 13, 1995

3. Report Type and Dates Covered.
Contractor Report

4. Title and Subtitle.
An Economic Analysis of Abyssal Seafloor Waste Isolation

5. Funding Numbers.

Contract	N00014-94-1-G913
Program Element No.	0603716D
Project No.	R3716
Task No.	
Accession No.	DN154-043
Work Unit No.	74-554G-A1

6. Author(s).
Di Jin, Hauke L. Kite-Powell, and James M. Broadus*

7. Performing Organization Name(s) and Address(es).
Woods Hole Oceanographic Institution
Office of Sponsored Projects
Woods Hole, MA 02543-1026

8. Performing Organization Report Number.

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217-5660

10. Sponsoring/Monitoring Agency Report Number.
NRL/CR/7401--95-0019

11. Supplementary Notes.

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*
This study describes an integrated analytical framework that captures the major economic, engineering, geographic, and social factors affecting the internal (direct) cost of abyssal seafloor waste isolation. We develop and apply computer models based on this framework to produce cost estimates for the disposal of sewage sludge and municipal incinerator ash via four deep ocean waste emplacement system concepts (surface emplacement, ROV glider, direct descent disc, and pipe riser) developed by Oceaneering Technologies. Our study focuses on five metropolitan areas (New York, Miami, Galveston, Los Angeles, and Seattle) and five proposed abyssal study sites identified by the Naval Research Laboratory's Abyssal Plains Waste Isolation Project, of which this work is one component.

Evidence suggests that the external (human and environmental health) costs of abyssal waste isolation are small compared to internal costs. However, the variance of external cost is large because our present state of knowledge about the fate and effect of waste in the ocean does not permit us to predict outcomes with certainty. Reducing this uncertainty is an important objective for future research. Assuming that external costs are not significantly higher, and that the marine transport concepts do not prove to be significantly more expensive than anticipated, abyssal ocean waste isolation would cost about $43 per ton for sludge and ash from the New York metropolitan area. This is competitive with present land-based disposal costs in New York City of over $160 per ton for sludge and over $48 per ton for ash. The abyssal ocean option may be less competitive in other metropolitan areas because of their more limited waste volumes. In extending the present work, opportunities exist to incorporate other waste streams (such as dredged material) into our models, and to refine the model's configuration of transport systems to particular waste stream volumes.

14. Subject Terms.
waste disposal; waste isolation; abyssal plains; deep ocean; sewage sludge; dredged material, fly ash

15. Number of Pages.
119

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
Unclassified	Unclassified	Unclassified	SAR

The work reported herein is part of the project "Technical and Economic Assessment of Storage of Industrial Waste on Abyssal Plains" managed by the Naval Research Laboratory and sponsored by the Strategic Environmental Research and Development Program.

EXECUTIVE SUMMARY

This study describes an integrated analytical framework that captures the major economic, engineering, geographic, and social factors affecting the internal (direct) cost of abyssal seafloor waste isolation. We develop and apply computer models based on this framework to produce cost estimates for the disposal of sewage sludge and municipal incinerator ash via four deep ocean waste emplacement system concepts (surface emplacement, ROV glider, direct descent disc, and pipe riser) developed by Oceaneering Technologies. Our study focuses on five metropolitan areas (New York, Miami, Galveston, Los Angeles, and Seattle) and five proposed abyssal study sites identified by the Naval Research Laboratory's Abyssal Plains Waste Isolation Project, of which this work is one component.

The unit cost of isolating a given waste stream in the abyssal ocean depends on many factors, including the size of the region from which waste is brought to the transshipment port, the distribution of waste-generating centers within the region, the technology used for transporting the waste to the seafloor, and the distance of the abyssal site from the port. Our findings indicate that the unit source-to-port transport cost using 30 cubic yard trucks is below \$10 per ton within a 50 mile radius and below \$20 per ton within a 100 mile radius of the port. Port-to-site unit cost, using the least expensive of Oceaneering's concepts (surface emplacement) and assuming transport from New York to NRL's Atlantic 1 site, is about \$33 per ton at relatively small volumes (sludge and fly ash from within a 50 mile radius of New York's harbor), and about \$23 per ton at larger volumes (100 mile radius).

Evidence suggests that the external (human and environmental health) costs of abyssal waste isolation are small compared to internal costs. However, the variance of external cost is

large because our present state of knowledge about the fate and effect of waste in the ocean does not permit us to predict outcomes with certainty. Reducing this uncertainty is an important objective for future research. Assuming that external costs are not significantly higher, and that the marine transport concepts do not prove to be significantly more expensive than anticipated, abyssal ocean waste isolation would cost about $43 per ton for sludge and ash from the New York metropolitan area. This is competitive with present land-based disposal costs in New York City of over $160 per ton for sludge and over $48 per ton for ash. The abyssal ocean option may be less competitive in other metropolitan areas because of their more limited waste volumes. In extending the present work, opportunities exist to incorporate other waste streams (such as dredged material) into our models, and to refine the model's configuration of transport systems to particular waste stream volumes.

Ultimately, each region's waste management problem should be analyzed in an optimization framework that considers the internal and external costs of the ocean option along with waste reduction and land-based disposal alternatives. At present, U.S. law prohibits the disposal of sewage sludge in the ocean, and ocean disposal of industrial waste may be phased out internationally under amendments to the London Dumping Convention. Legal and policy aspects of the ocean option, and in particular the role of public perceptions and political forces in shaping its future viability, are an important area for further research.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Dr. Philip Valent, Mr. Martin Fagot and Mr. William Sawyer of NRL, and to Dr. Andrew Solow of WHOI, for helpful comments and discussions; and to Mr. Michael Hightower, Mr. William Richards and Ms. April Marcy of Oceaneering Technologies for providing us with engineering/cost data for the marine system concepts. This research is supported by a grant from the Naval Research Laboratory (No. N00014-94-1-G913).

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1. INTRODUCTION

This report has been prepared by the Marine Policy Center (MPC) at the Woods Hole Oceanographic Institution (WHOI) as part of the Naval Research Laboratory (NRL)'s Abyssal Plains Waste Isolation Project. The report documents results of MPC's research on source-to-port and port-to-site waste cycle costs, and on the development of an optimal multimedia waste management strategy.

Investigation of the ocean option in an overall strategy for waste management is motivated by a combination of observed trends (MPC 1993):

- growing populations and associated growth in the waste loads generated by society,
- limited physical resources (such as landfill sites) to receive these wastes,
- heightened sensitivity to the public health and environmental risks of waste disposal,
- increasing resistance to specific waste disposal proposals and tightened restrictions on disposal options,
- rising disposal costs, and
- arguably premature removal of ocean disposal options through legal and regulatory actions.

Out of a total U.S. waste generation in excess of 12 billion tons per year, five waste streams, exceeding a total of 765 million tons per year, present perhaps the greatest management challenge: (i) sewage sludge, (ii) municipal solid waste, (iii) ash, (iv) industrial toxic waste, and (v) dredged material (Jin *et al.* 1993). Sewage sludge, municipal solid waste, and ash are expected to increase in volume in the future, while toxic waste and dredged material may level off or even decline. Current management of these waste streams includes multimedia disposal,

recycling, energy recovery, and other beneficial uses. Three media are used for disposal: (i) land (landfill, other surface disposal, and underground injection), (ii) air (incineration and other emission), and (iii) water (public sewage and surface water). With the termination of U.S. ocean dumping of industrial waste in 1988 and of sewage sludge in 1992, dredged material is the only U.S. waste still legally dumped in the ocean.

A number of ocean scientists, however, believe that some ocean sites may offer the best solution for disposal of some wastes. This belief is based on a recognition that the ocean covers over 70% of the planet's surface, containing a vast variety of potential disposal sites and some of the environments farthest removed from possible feedbacks harmful to humans. Scientific understanding of these environments has increased in the last 30 years, to a level where ocean scientists can now suggest which ocean settings may be suitable sites for the isolation of certain wastes. This knowledge, together with recognition that all waste management options pose some threat to the environment and human health, suggests that consideration of ocean options may lead to reduced risk and improved future waste management.

Prior to this NRL project, the most comprehensive economic and policy study of the ocean option for waste management (WHOI 1993) was organized by the Marine Policy Center. The 1993 study consists of research conducted at MPC (Jin *et al.* 1993) and by associated researchers (Farrow 1992; Sigman 1993). The conclusions of the study are summarized in the following points (MPC 1993):

- Optimal waste management employs the multi-media combination of options, including waste reduction and beneficial uses, that minimizes total cost, including (i) *internal costs* such as transportation, processing, and disposal cost; and (ii) *external costs* such as damage to human

health and the natural environment.

• Earlier studies (Gift *et al.* 1989; Huetteman *et al.* 1989) concluded that sewage sludge can be disposed of in certain coastal ocean sites in an environmentally sound manner with lower health risks and lower internal costs than alternative disposal options. Very preliminary estimates produced at WHOI have indicated that a large-scale operation might be economically feasible even for abyssal ocean sludge disposal. However, studies have also shown that cost estimates for projects using commercially unproven technologies are not only characteristically biased low, but are so uncertain that they cannot be relied upon at all (Merrow, Chapel, and Worthing, 1979; Merrow, Phillips, and Myers, 1981).

• Because of transportation distance alone (1000 km from land), abyssal ocean disposal may not have even any (internal) cost advantage over land-based alternatives. At the same time, waste reduction (source reduction, recycling) and beneficial use provide an important and promising avenue for further gains in optimizing waste management, and it appears feasible to resolve the waste management crisis effectively using only land-based technologies, through a combination of waste reduction and interstate waste shipment.

• The total cost of the deep ocean option is location specific, subject to large uncertainty about environmental costs, *and warrants more careful study.* To the extent that there is uncertainty about the benefits of leaving abyssal ocean sites unspoiled, forbearance (which brings exogenous increases in knowledge) and further research should reduce that uncertainty. To the extent uncertainty surrounds the internal and external costs of abyssal ocean disposal, this uncertainty could be reduced by experimental development and study of the ocean option while preserving the option of not pursuing full development if the results are discouraging.

The NRL project, organized by the Laboratory's Marine Geosciences Division, is designed to conduct an assessment of the abyssal ocean waste management option, focusing on deep ocean isolation of sewage sludge, fly ash from municipal incinerators, and dredged material. The objective of this NRL project is to assess the concept of isolating these wastes at abyssal plain depths on the ocean floor, and to identify the advantages, disadvantages, and economic and environmental viability of this alternative. Specifically, the NRL project consists of five task areas: environmental assessment, engineering assessment, site survey, monitoring program, and economic analysis. The research activities include review of relevant past studies and concepts, compilation and analyses of existing environmental data, analyses and assessment of technical feasibility, and identification of feasibility and risk in environmental, technical and cost areas.

MPC's contribution to the NRL project is primarily in the economic task area. The objectives of this MPC study are to

• identify major economic, engineering, geographic and social factors affecting the costs associated with abyssal seafloor waste isolation;

• develop an integrated analytical framework which captures these factors and can be used to generate quantitative estimates of the *internal* cost of a waste management option;

• apply this framework to the abyssal ocean option and develop systematic cost estimates for engineering systems transporting wastes from sources to a port and from that port to an abyssal ocean disposal site; and

• analyze the cost of the abyssal ocean option in the context of a multimedia waste management framework and assess the cost competitiveness of the ocean option.

This report focuses on the cost assessment for abyssal seafloor waste isolation. Cost estimates are presented for five metropolitan areas: New York, Miami, Galveston, Los Angeles and Seattle. For a detailed discussion of waste generation and management in the United States, and related economic and policy issues, the reader is referred to the WHOI (1993) report. Although the WHOI (1993) study summarized substantial cost data related to several waste management alternatives, no cost estimation was developed specifically for the abyssal ocean option. Thus, the present study has extended significantly our earlier work, especially in understanding the internal cost associated with the abyssal ocean option.

The remainder of this report is organized as follows. Section 2 describes waste quantity estimation in the five metropolitan areas. Section 3 presents cost assessment procedures, including research methodology, model-building, data collection and analysis, and simulation results. Section 4 discusses the abyssal ocean option in a multimedia framework and reviews the policy constraints facing ocean disposal. Conclusions are developed in Section 5. Primary data and computer programs are included in Appendixes 1 through 3.

2. WASTE VOLUMES IN FIVE METROPOLITAN AREAS

In the late 1980s, 11 to 12 billion tons of nonhazardous waste and 0.7 billion tons of hazardous waste (using Resource Conservation and Recovery Act of 1976 definitions) were generated annually in the United States (OTA 1992). Sources of these wastes include industry, agriculture, and municipalities. Management of these wastes depends on waste type and characteristics, location, and costs. For most waste types, management practices include multimedia disposal, recycling, energy recovery, and other beneficial uses (WHOI 1993).

As waste management costs are location and waste-specific, it is necessary to focus our study on selected representative regions. Ideally, a region's wastes would be managed using the set of disposal options that minimize total costs, loosely defined to include both private (internal) costs and all environmental (external) costs. Thus, a sound waste management strategy should consider both all currently used and all potential management and disposal technologies. Abyssal seafloor waste isolation is addressed in this study as a possible disposal alternative within a set of management options.

The NRL project has identified five potential abyssal sites: two in the Atlantic Ocean (Atlantic 1 (28°N, 70°W) and Atlantic 2 (27°N, 61°W)), one in the Gulf of Mexico (Gulf (25°N, 93.5°W), and two in the Pacific Ocean (Pacific 1 (33.5°N, 124°W) and Pacific 2 (35°N, 134°W)). To cover different geographic regions and major metropolitan areas, five ports are selected as study regions: New York, Miami, Galveston, Long Beach (Los Angeles) and Seattle.

The specific waste streams examined by the NRL project are sewage sludge, fly ash from municipal incinerators and contaminated dredged material. This report provides quantitative estimates for sludge and ash volumes in the five regions. It does not address contaminated

dredged material due to a lack of data.

As noted, the cost of abyssal ocean waste isolation consists of two parts: cost from source to port and cost from port to abyssal site. The terrestrial and marine segments employ trucks and barges, respectively. The cost of managing a waste stream is influenced by its volume. Thus, it is important to develop accurate estimates of waste volumes for the region in question. From an economic point of view, the boundary of the region depends primarily on land transportation cost. The lower the cost, the larger the region from which waste may economically be shipped to the port. Therefore, it is necessary to estimate total waste volumes as a function of distance from the outer boundary of the region to its port (radius from the port). As the distance increases, the total volume rises.

Ideally, the most accurate estimate can be obtained by identifying the location (distance from port) and waste throughput of individual waste management facilities. However, this is not always feasible within the scope of this study. Alternatively, a population-based measure may be used (for example, see Pennsylvania Department of Environmental Resources, n.d.b). In this study, we use a population-based measure for sewage sludge, because the number of treatment plants is large (over 12,000 publicly owned treatment works nationwide). Since the number of municipal incinerators is comparatively small (fewer than 200 nationwide), we estimate ash volumes for the five regions using data from individual facilities. Also, incineration is only one of several management technologies for municipal solid waste. While it is appropriate to use a population based measure to estimate municipal solid waste volumes, this method is not applicable to incinerator ash.

2.1. Sewage Sludge

The quantity of municipal sewage sludge generated in the United States almost doubled between 1972 and 1992. Currently, 5.4 million dry metric tons of sewage sludge are generated each year from approximately 12,750 publicly owned treatment works (POTWs). This translates to 47 pounds for every individual in the country (EPA 1992).

In this study, we focus on five ports: New York, Miami, Galveston, Los Angeles and Seattle. We estimate sludge volumes in the associated regions as the product of regional population and per capita sewage sludge generation (47 pounds per year).

According to the 1990 census, the New York metropolitan area is the most densely populated in the United States, followed by the Los Angeles area. The other three areas have significantly smaller populations, as shown in Table 1. To develop population distribution profiles for each of the five ports, we use the 1990 census data, with the county as the geographic unit. For transport distance, we use the mileage from the county seat to the region's port. Since some cities and towns in the county are closer to the port than the county seat while others are farther away, this assumption is reasonable for the purpose of this study. The mileages are from Rand McNally (1993) and represent the shortest, most direct highway distance between the cities over interstate, federal or primary state highways. Bayonne is taken as the port for the New York area, and Long Beach as the port for the Los Angeles area, while Miami, Galveston, and Seattle are straightforward.

We have developed a database for each of the five ports. In the database, each county is an observation described by five variables: state name, county name, population in the county, county seat name, and distance from county seat to port. These primary data are presented in

Table 1. Population in Five Metropolitan Areas (million)

Metropolitan Areas	Population
New York-Northern New Jersey-Long Island	19.342
Los Angeles-Riverside-Orange County	14.532
Houston-Galveston-Brazoria	3.731
Miami-Fort Lauderdale	3.193
Seattle-Tacoma-Bremerton	2.970

Tables A1 through A5 in Appendix 1. Population distribution profiles for the five ports are illustrated in Figures 1 through 5. In these Figures, each dot represents one county.

Figure 1 indicates that in New York, there are 18 counties within a 50 mile radius of the port, five of them with population over one million. There are other major cities, such as Philadelphia, within a 100 mile radius. Population density declines only slowly as distance increases. This population profile helps explain why New York City has the highest per unit waste disposal cost in the United States: space for land treatment and disposal facilities is at a premium.

The other four ports, as depicted in Figures 2 through 5, have a different profile. Population density declines more quickly as distance increases in these regions. This suggests that land space for waste management facilities may be more readily available in these areas. Population distributions by distance from the five ports are summarized in Table 2 and Figure 6.

Using the population data presented in Appendix 1 and the per capita sludge generation estimate, we calculate the cumulative sewage sludge volume by distance from port for the five areas. Per capita sludge generation is 47 pounds (at 100 percent solid) per year. In our volume estimates, sewage sludge volumes are computed as 20 percent solid.

The results are presented in Figures 7 through 11. As these figures show, the cumulative sludge volume in the New York area increases steadily as the radius from the port increases from 0 to 200 miles. Because of the underlying population profiles, cumulative sludge volume increases much more rapidly beyond 50 miles in the New York area than in the other regions.

Figure 1. Population Distribution by Distance, Port of New York

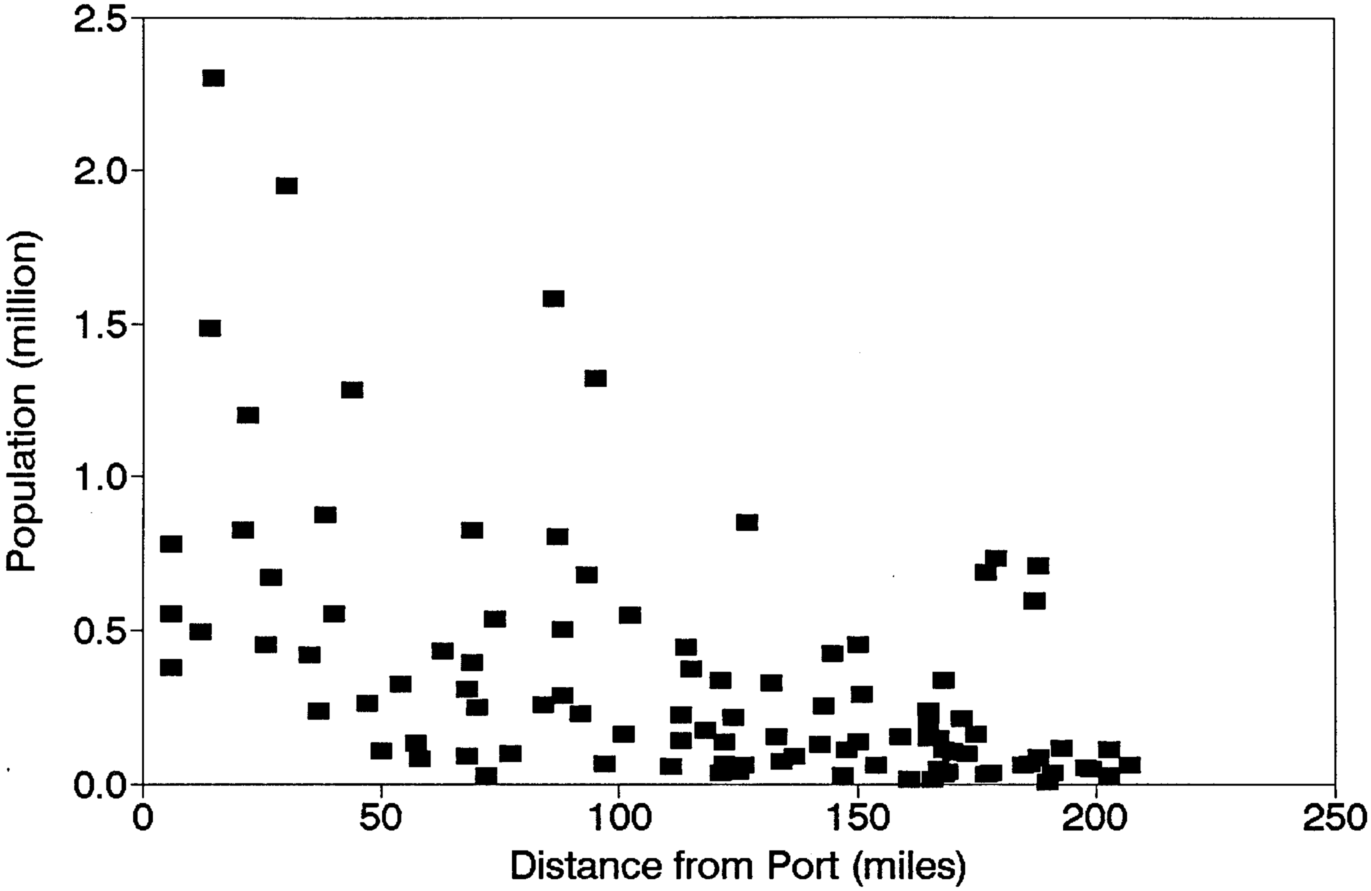


Figure 2. Population Distribution by Distance, Port of Miami

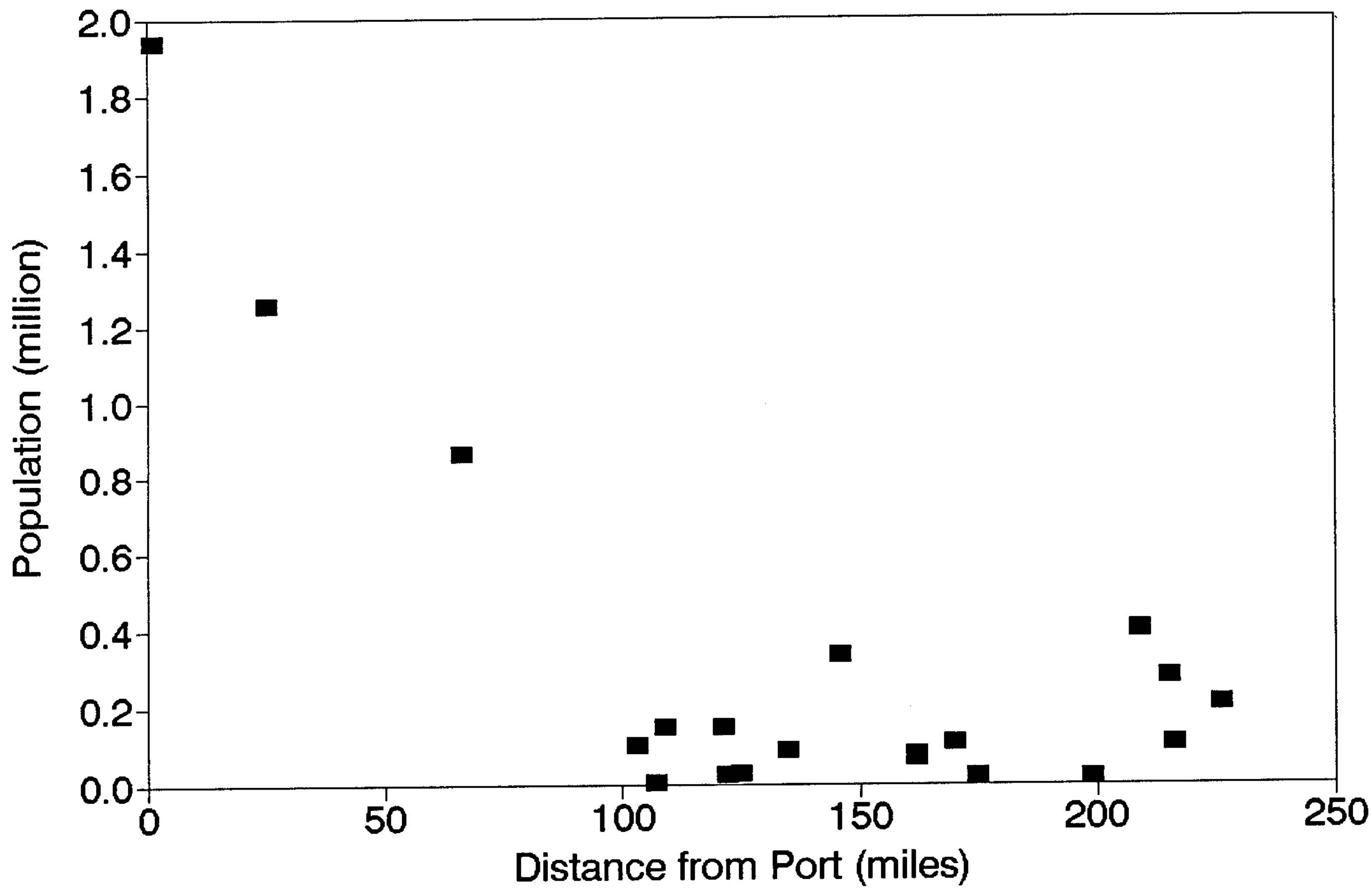


Figure 3. Population Distribution by Distance, Port of Galveston

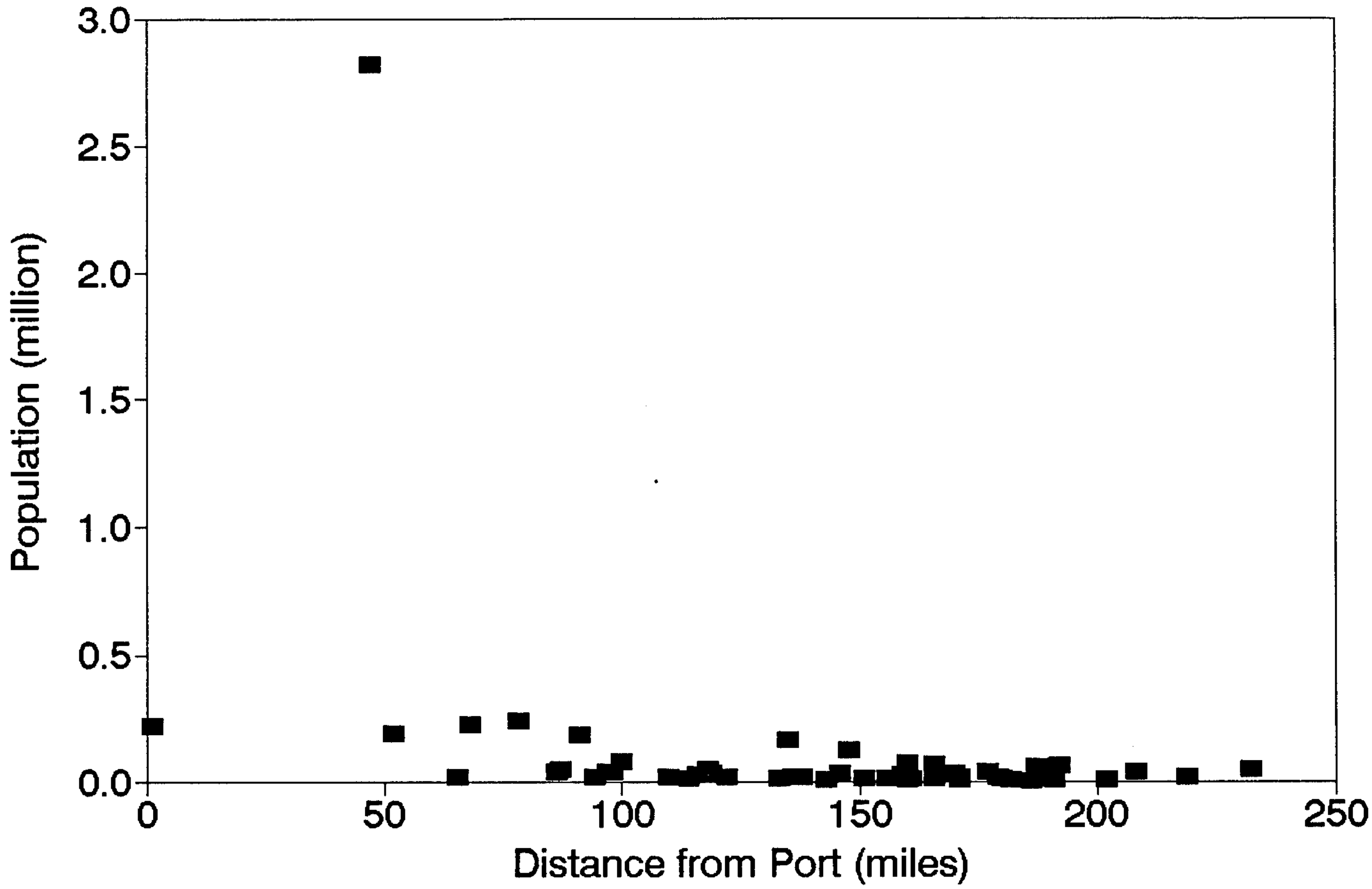


Figure 4. Population Distribution by Distance, Port of Long Beach

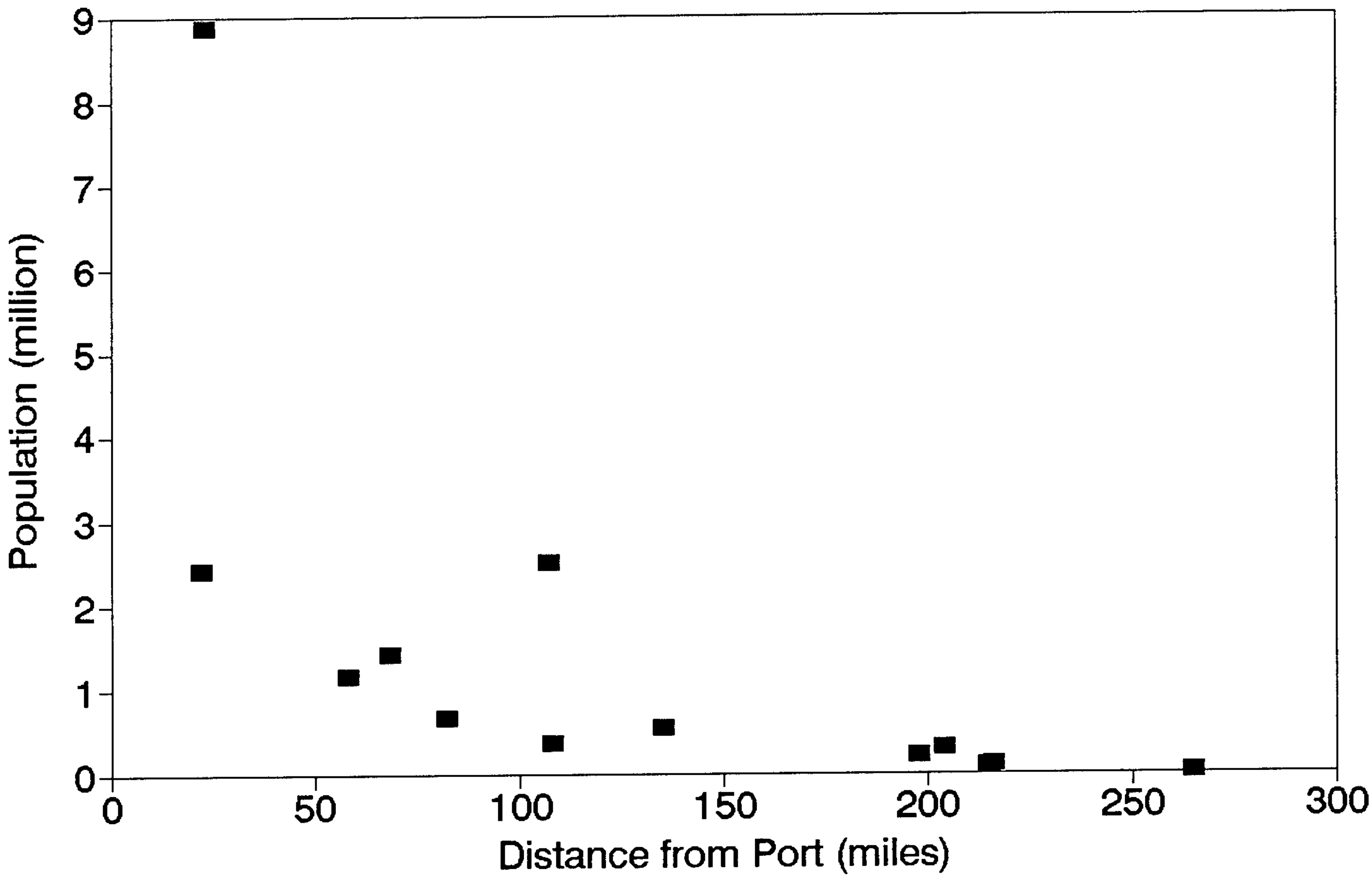


Figure 5. Population Distribution by Distance, Port of Seattle

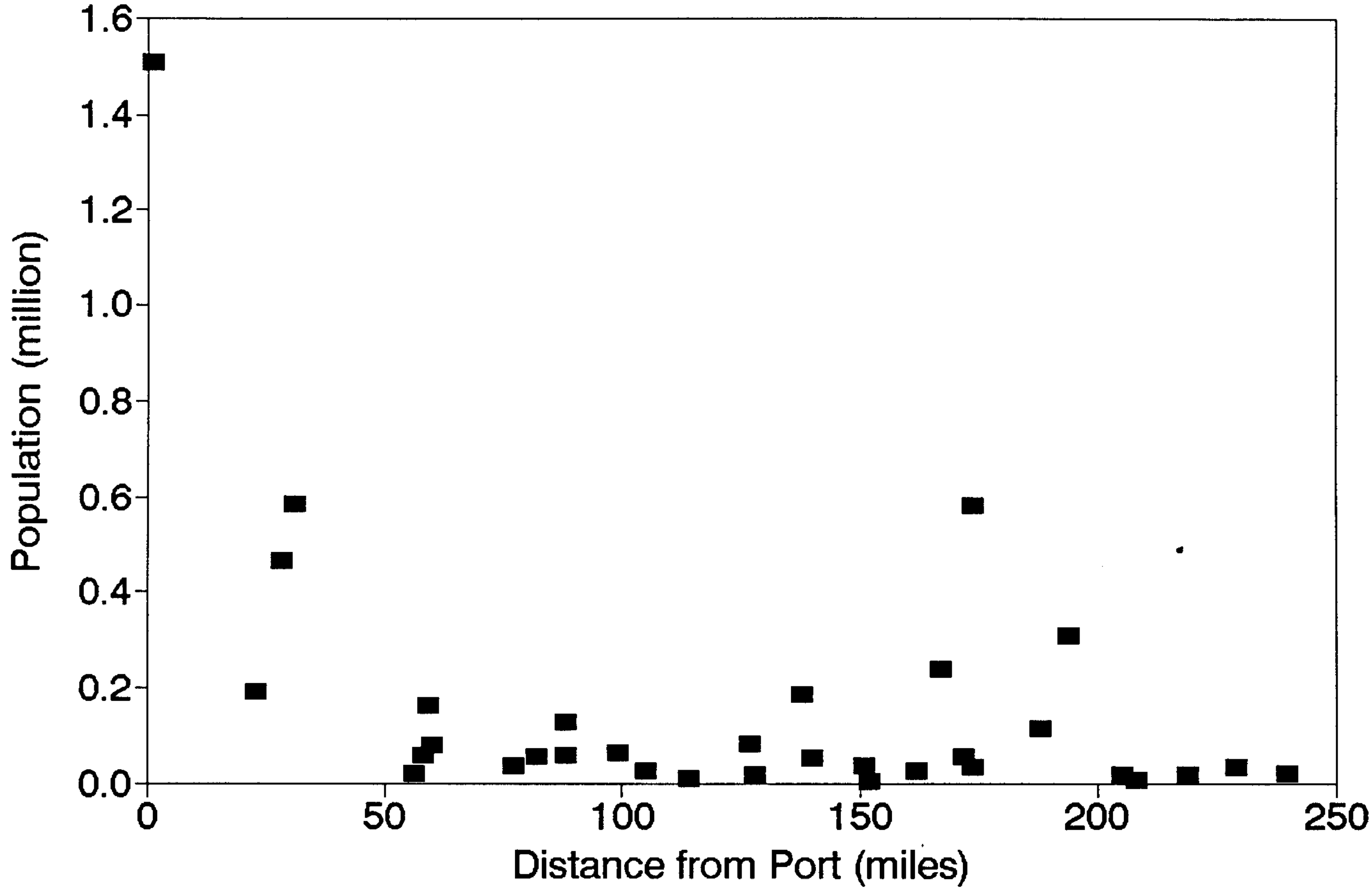


Table 2. Population Distribution by Distance from Ports

Distance	New York	Miami	Galveston	Long Beach	Seattle
0-50	14848983	3192712	3035595	11273720	2748881
51-100	9250153	863503	1133687	3257809	667248
101-150	6080430	891482	545294	3411605	378834
151-200	5799053	300795	703318	217162	1401242

Figure 6. Population Distribution by Distance from Ports

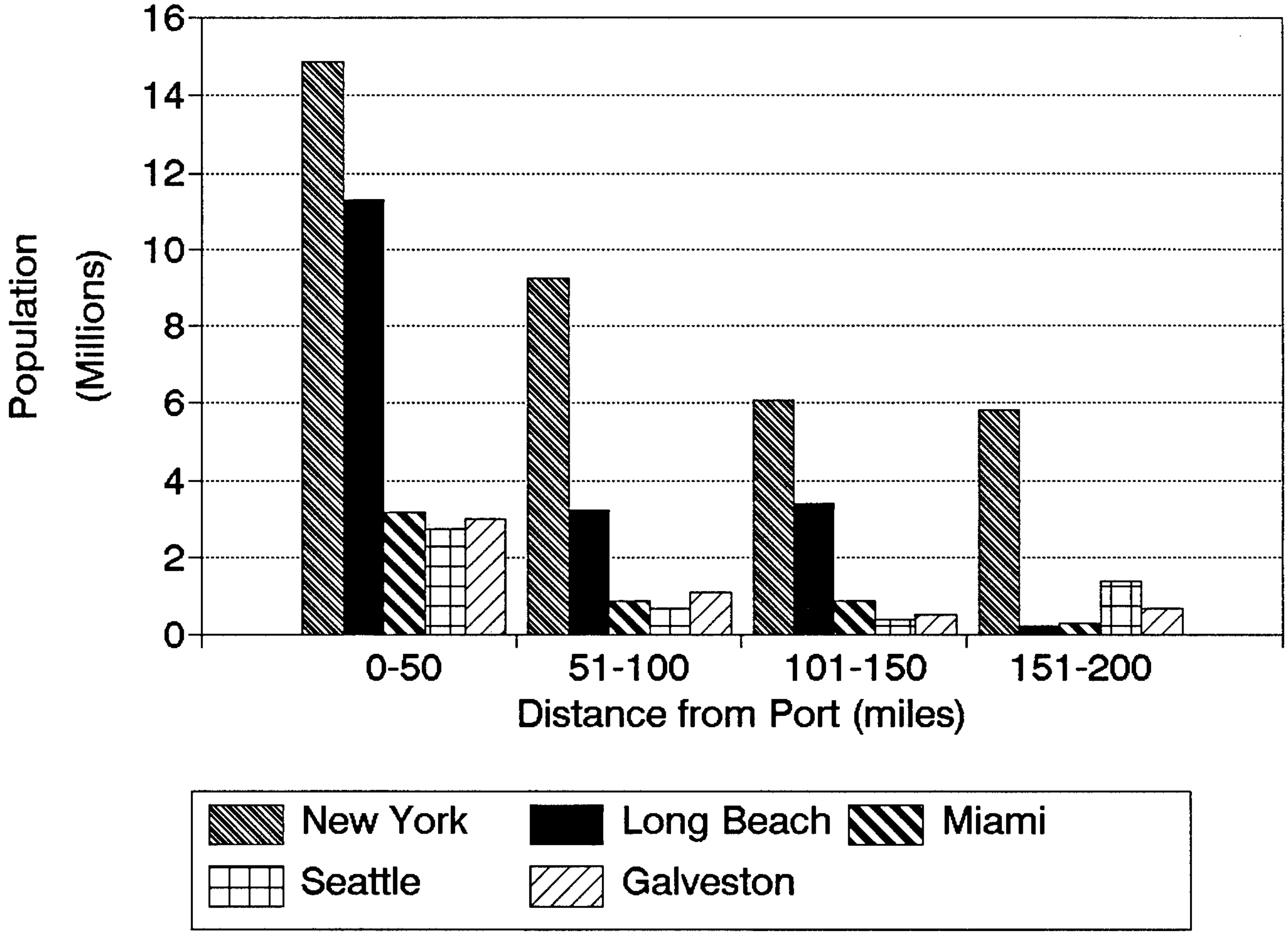


Figure 7. Cumulative Sludge Volume by Distance from Port of New York

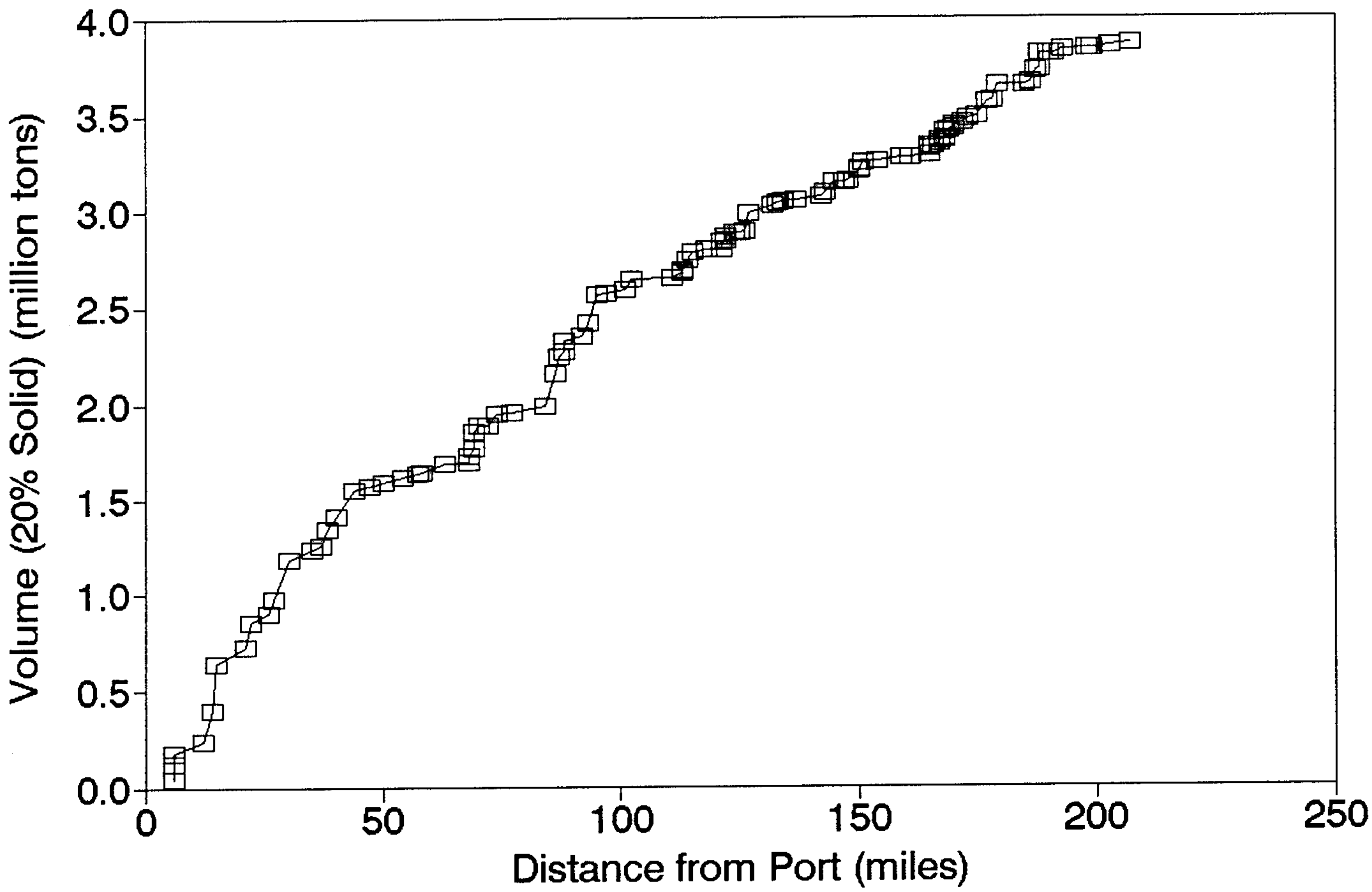


Figure 8. Cumulative Sludge Volume by Distance from Port of Miami

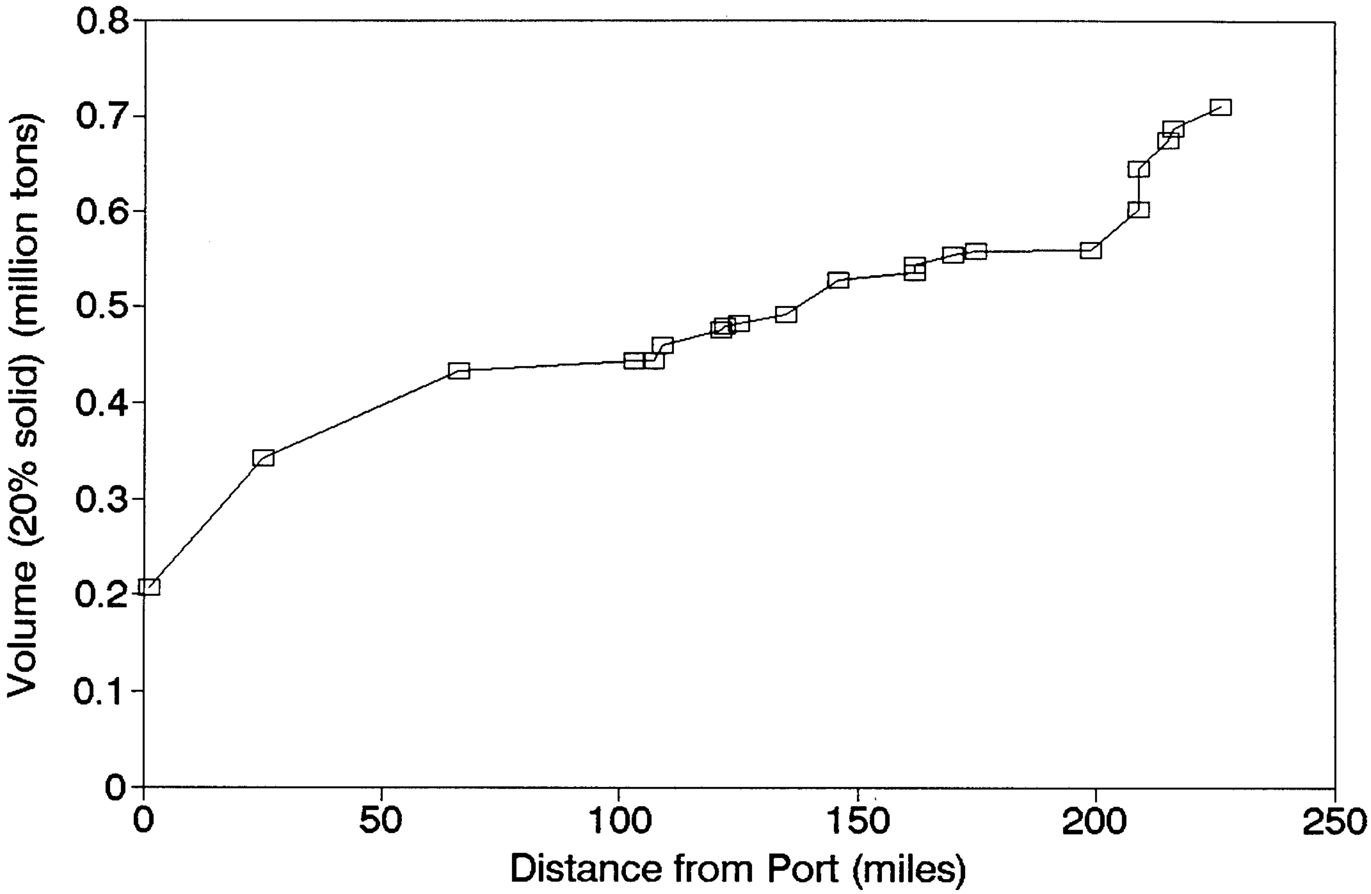


Figure 9. Cumulative Sludge Volume by
Distance form Port of Galveston

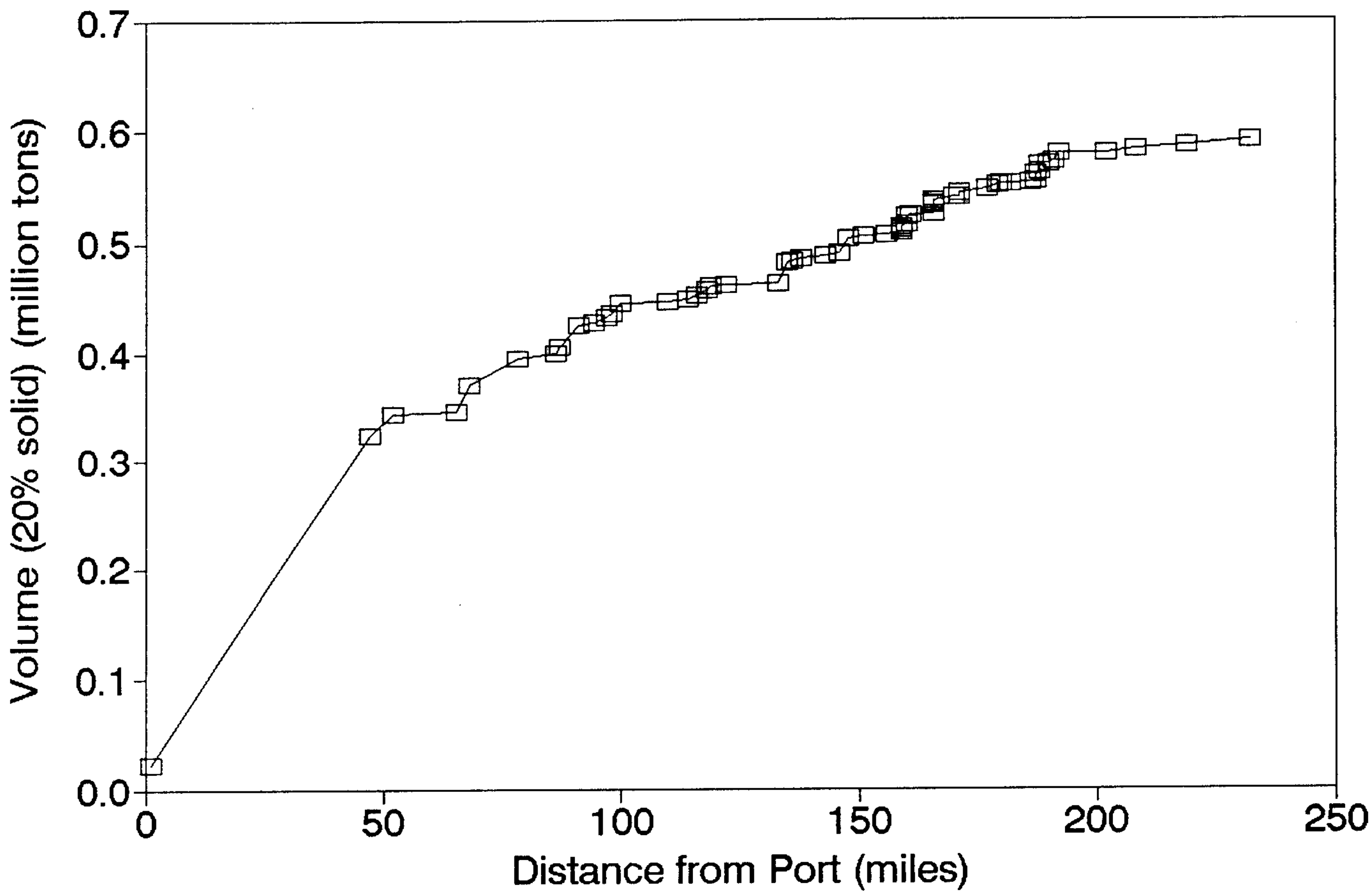


Figure 10. Cumulative Sludge Volume by Distance from Port of Long Beach

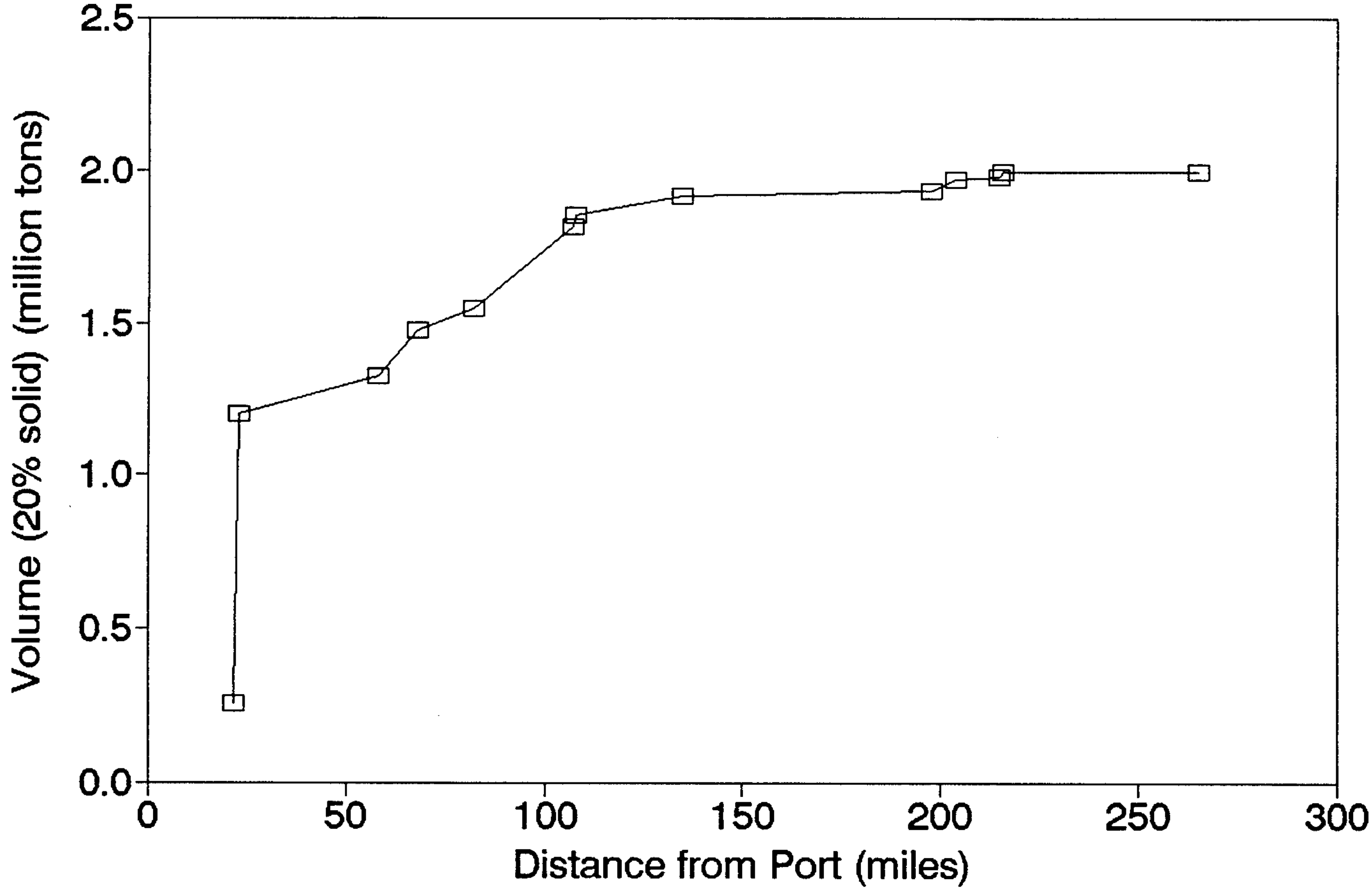
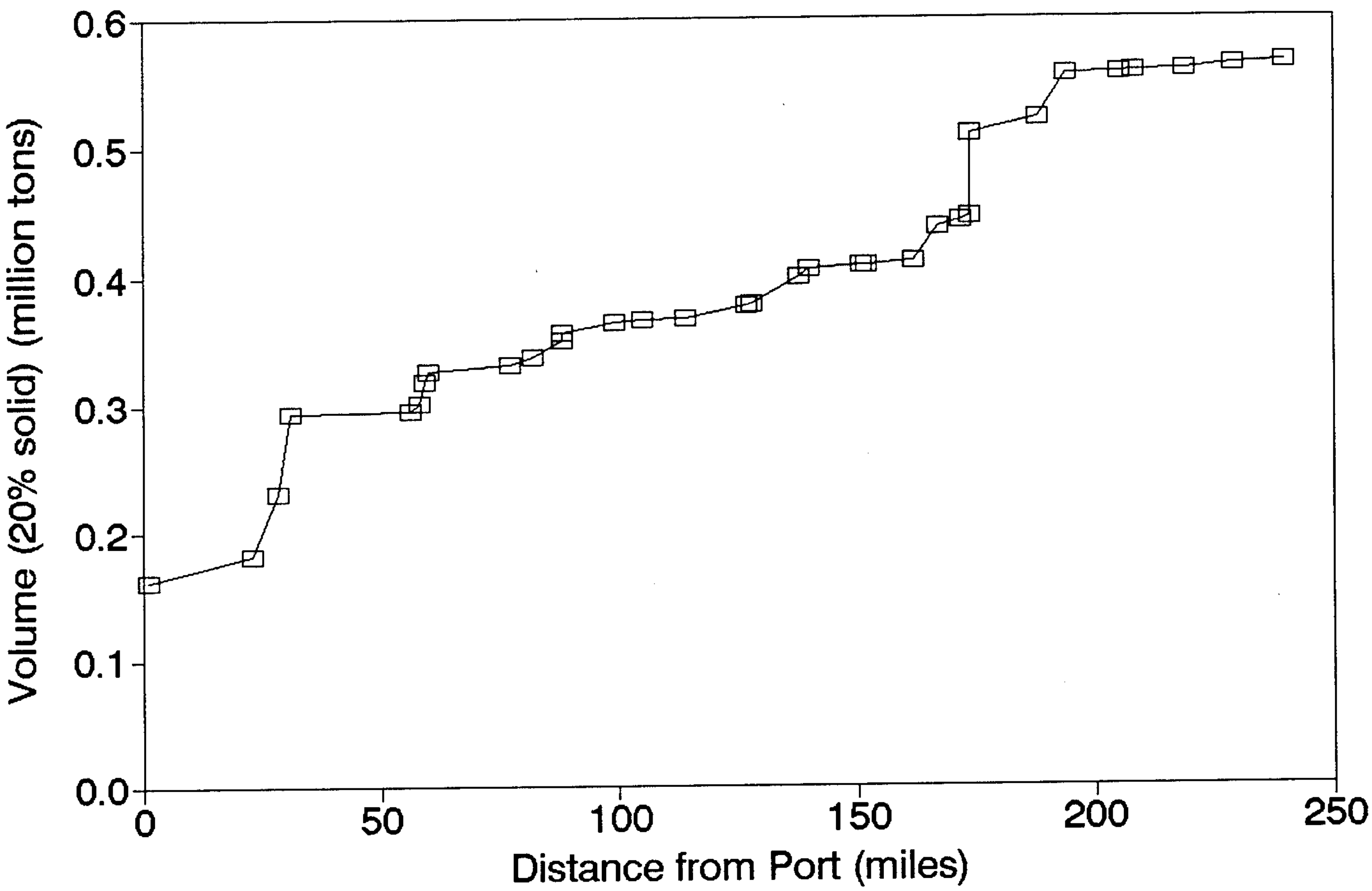


Figure 11. Cumulative Sludge Volume by Distance from Port of Seattle



2.2. Ash from Municipal Incinerators

As noted, we develop ash volume estimates using data for individual incinerators from Berenyi and Gould (1993). In the United States, there are 171 existing and planned resource recovery facilities which incinerate solid waste and generate electricity, steam and fuel. Thirty-seven percent of these are located in the Northeast. Total national combined ash (bottom and fly ash) generation is 28,131 tons per day (on a wet basis). The average plant generates 176 tons of combined ash per day, with figures ranging from one ton to 935 tons per day. The wet ash residue, on average, comprises 23.1 percent of the weight of the incoming municipal solid waste (Berenyi and Gould 1993). There are also fewer than 30 waste incinerators with no energy recovery (Governmental Advisory Associates 1994). Most of them are small and, therefore, not considered in this study.

Incinerators in the New York area are summarized in Table 3. The first two columns show the state and city where an incinerator is located. Several plants are in the advanced planning stage; their scheduled opening years are noted in the second column, next to the city name. The third column is the distance (in miles) from the incinerator to the port. The fourth column is combined ash output in tons per day. Also included in the Table are the ash disposal fee (including transportation cost) for each incinerator, and the tipping fees that incinerators charge to haulers who deliver municipal solid waste to their plants. Generally, the disposal fees within a 100 mile radius of the ports are higher than those at distances close to 200 miles. The tipping fees are influenced not only by fees charged by nearby alternative facilities, such as landfills or recycling plants, but also by capital investment in the plants. Thus, the trend in tipping fees at different distances is less obvious than that in disposal fees.

Table 3. Incinerators, Port of New York

STATE	CITY	DISTANCE	ASH VOLUME TON/DAY	DISPOSAL FEE $/TON	TIPPING FEE $/TON
NJ	NEWARK	6	600	88.00	75.39
NJ	KEARNY (96)	9	380	-	76.00
NY	BROOKLYN (99)	15	935	-	80.00
NJ	RAHWAY (94)	17	367	37.00	72.00
NY	QUEENS	30	167	-	-
NY	LONG BEACH	39	45	-	76.92
NY	WESTBURY	44	651	69.00	24.61
NY	GLEN COVE	47	66	-	93.18
NJ	HAMILTON TOWNSHIP (96)	51	310	56.00	100.00
NY	PEEKSKILL	54	414	-	23.00
NY	WEST BABYLON	58	160	-	66.66
NY	EAST NORTHPORT	61	185	-	66.66
NJ	WRIGHTSTOWN	65	8	49.00	-
NJ	OXFORD TOWNSHIP	68	113	-	116.67
CT	BRIDGEPORT	69	507	19.30	69.00
PA	GLENDON (96)	70	106	-	80.00
NY	RONKONKOMA	71	137	40.00	87.18
NY	POUGHKEEPSIE	84	110	104.00	90.25

Table 3. Incinerators, New York (Continued)

STATE	CITY	DISTANCE	ASH VOLUME TON/DAY	DISPOSAL FEE $/TON	TIP. FEE $/TON
NJ	CAMDEN	88	274	55.00	79.77
NJ	WEST DEPTFORD TOWNSHIP	93	179	20.00	98.50
PA	CONSHOHOCKEN	93	291	54.00	63.50
CT	WALLINGFORD	101	118	15.50	72.82
PA	CHESTER	102	685	50.00	61.54
CT	BRISTOL	110	115	40.00	50.00
PA	STOWE	112	383	-	-
DE	NEW CASTLE	120	-	-	57.64
DE	NEW CASTLE	120	120	-	66.12
CT	HARTFORD	127	410	-	51.00
CT	NORTH WINDHAM	149	36	32.00	101.28
CT	PRESTON	149	162	61.40	79.00
CT	LISBON (95)	149	106	60.00	70.00
MA	AGAWAM	150	109	24.00	46.15
MA	PITTSFIELD	150	86	-	68.72
NY	ALBANY	151	-	55.00	55.00
NY	ALBANY	151	89	64.05	-
PA	MARIETTA	159	280	-	69.00
NY	GREEN ISLAND (96)	160	383	-	75.00

Table 3. Incinerators, New York (Continued)

STATE	CITY	DISTANCE	ASH VOLUME TON/DAY	DISPOSAL FEE $/TON	TIPPING FEE $/TON
MD	JOPPA	161	144	21.77	35.90
CT	STERLING	164	92	40.00	60.00
PA	HARRISBURG	165	150	-	56.41
PA	YORK	168	273	-	56.00
RI	NORTH KINGSTON (96)	177	129	24.00	80.00
MD	BALTIMORE	179	539	10.02	34.39
MD	COCKEYSVILLE	184	-	-	46.15
RI	JOHNSTON	187	173	24.00	80.00
MA	MILLBURY	188	396	-	70.00

Similar data for incinerators in three of the other regions are shown in Table 4. There are no resource recovery facilities located within 200 miles of Galveston. Tables 3 and 4 indicate that ash disposal fees along the east coast are significantly higher than those on the west coast, with the highest being in the Northeast. This is not surprising considering the population density in the region.

We use the data in Tables 3 and 4 to generate plots of cumulative combined ash volume versus distance from port for the four areas, as shown in Figures 12 through 15. Like sewage sludge, cumulative ash volume rises steadily as distance increases in the New York area (Figure 12). In other regions, most ash is generated within 50 miles of the port. In Los Angeles and Seattle, the ash volumes are small.

Total waste volumes within 50 and 100 mile radii of the five ports are summarized in Tables 5 and 6. In both Tables, the sludge is at 20 percent solid and the ash is "wet". We consider two distinct scenarios: (i) transporting dewatered sludge and combined ash, and (ii) transporting sludge and fly ash only (calculated as 20 percent of the combined ash).[1] As shown in Tables 5 and 6, the New York area has the largest waste volume. The total volume of sludge and combined ash in the area increases from 2.8 million tons to 4.8 million tons when the radius rises from 50 miles to 100 miles. The total waste volumes in the other four regions are significantly smaller and they are concentrated within 50 miles of the ports. At a 100 mile radius, Los Angeles has less than 2 million tons of sludge and combined ash, Miami has 1.2 million tons, and Galveston and Seattle each has less then 0.5 million tons.

It should be pointed out that while the above sludge volume estimates are accurate enough

[1] Fly ash may pose a greater threat to the environment than bottom ash.

Table 4. Incinerators, Other Ports

STATE	CITY	DISTANCE	ASH VOLUME TON/DAY	DISPOSAL FEE $/TON	TIPPING FEE $/TON
Port of Miami					
FL	MIAMI	1	513	-	46.15
FL	PEMBROKE PINES	17	216	65.00	56.41
FL	FORT LAUDERDALE	25	576	-	63.40
FL	POMPANO BEACH	35	480	40.00	63.40
FL	WEST PALM BEACH	66	263	-	91.28
FL	FT. MYERS (95)	146	223	-	60.00
FL	KEY WEST	162	36	-	199.99
FL	LAKELAND	220	14	31.00	19.00
Port of Long Beach					
CA	LONG BEACH	1	482	15.90	27.89
CA	COMMERCE	22	98	-	34.87
Port of Seattle					
WA	TACOMA	31	238	-	48.00
WA	TACOMA	31	30	5.00	-
WA	FORT LEWIS	35	28	-	-
WA	MOUNT VERNON	60	28	-	82.05
WA	FERNDALE	96	25	-	93.27

Figure 12. Cumulative Ash Volume by Distance from Port of New York

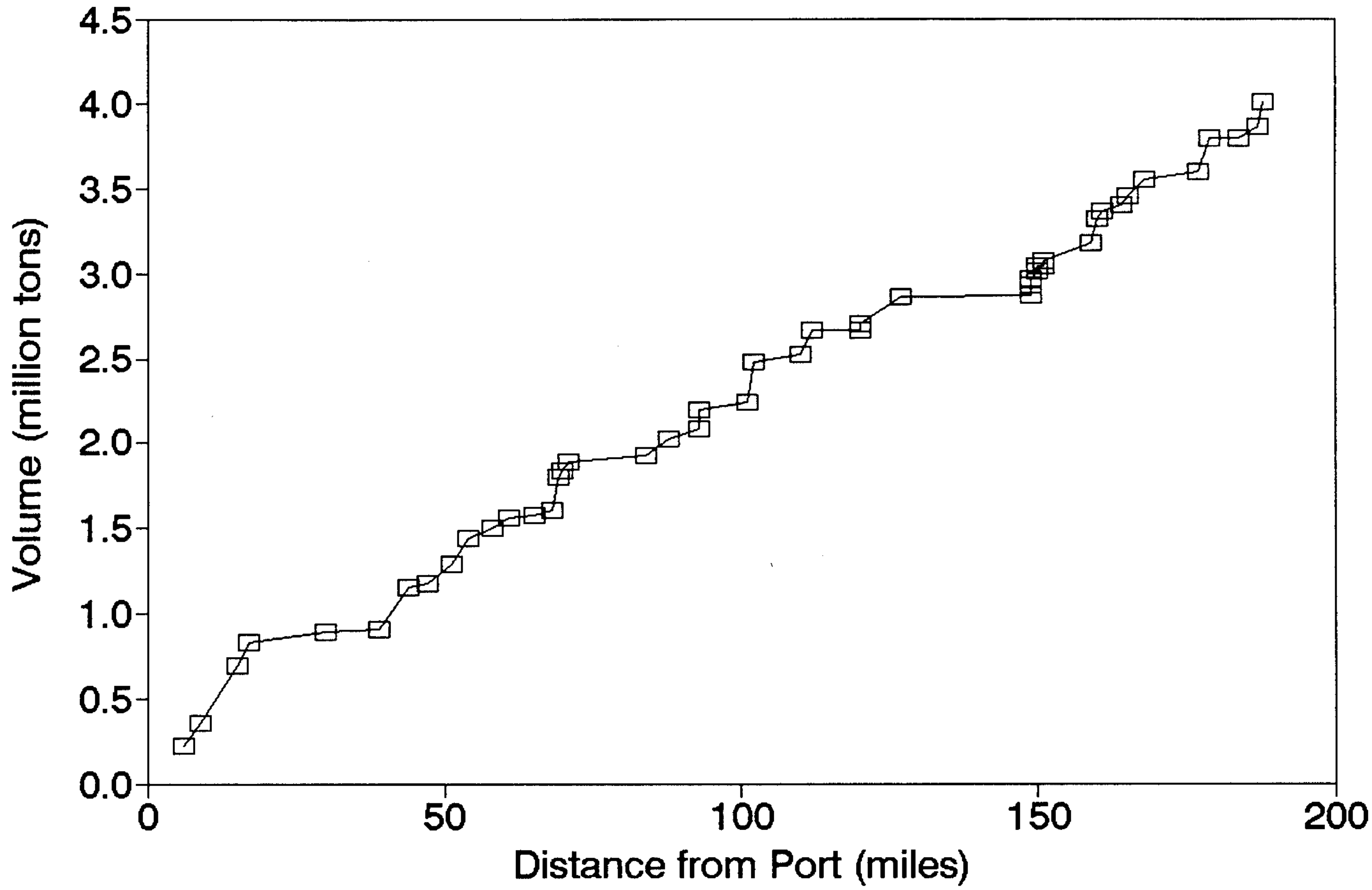


Figure 13. Cumulative Ash Volume by Distance from Port of Miami

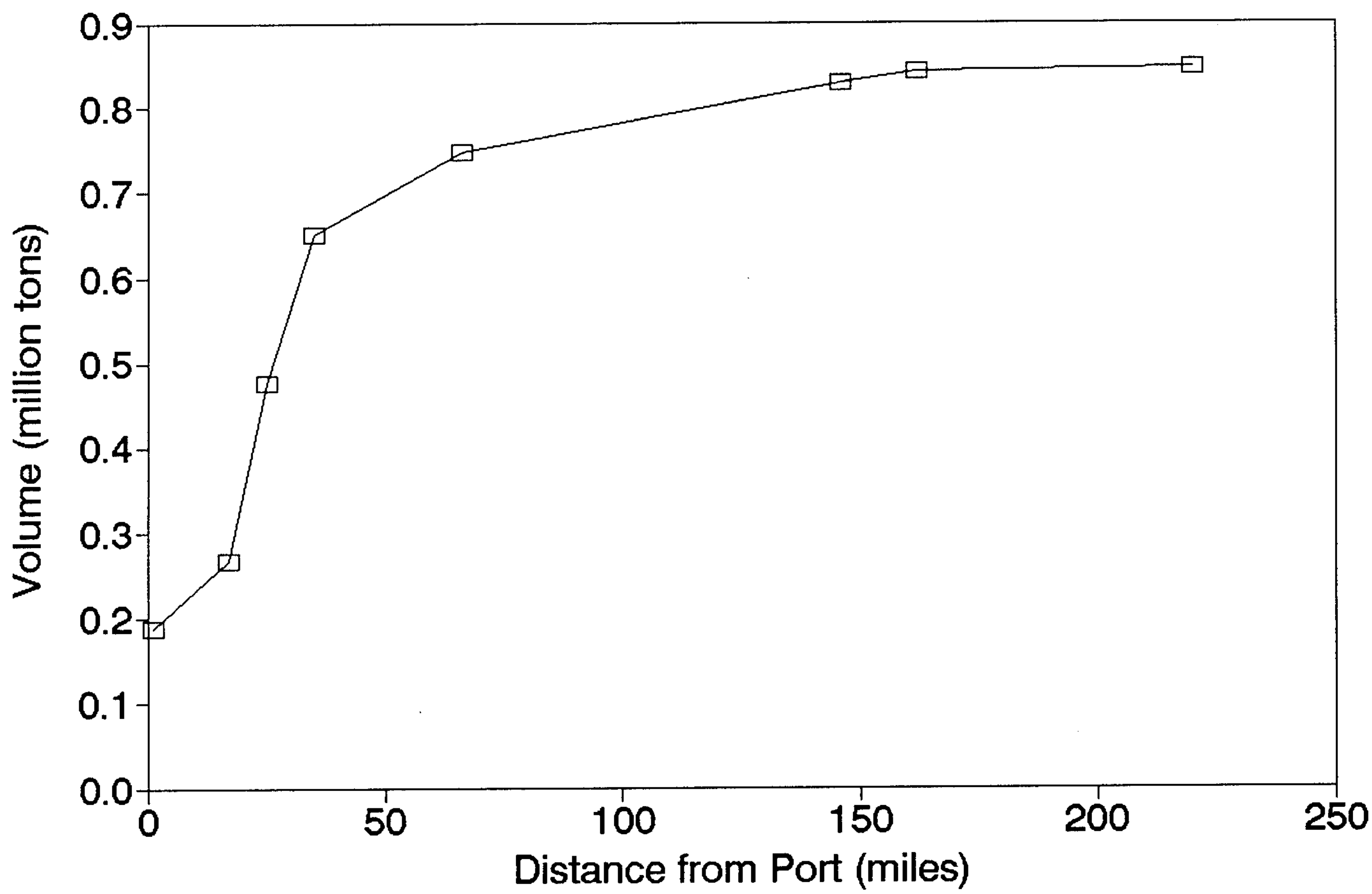


Figure 14. Cumulative Ash Volume by Distance from Port of Long Beach

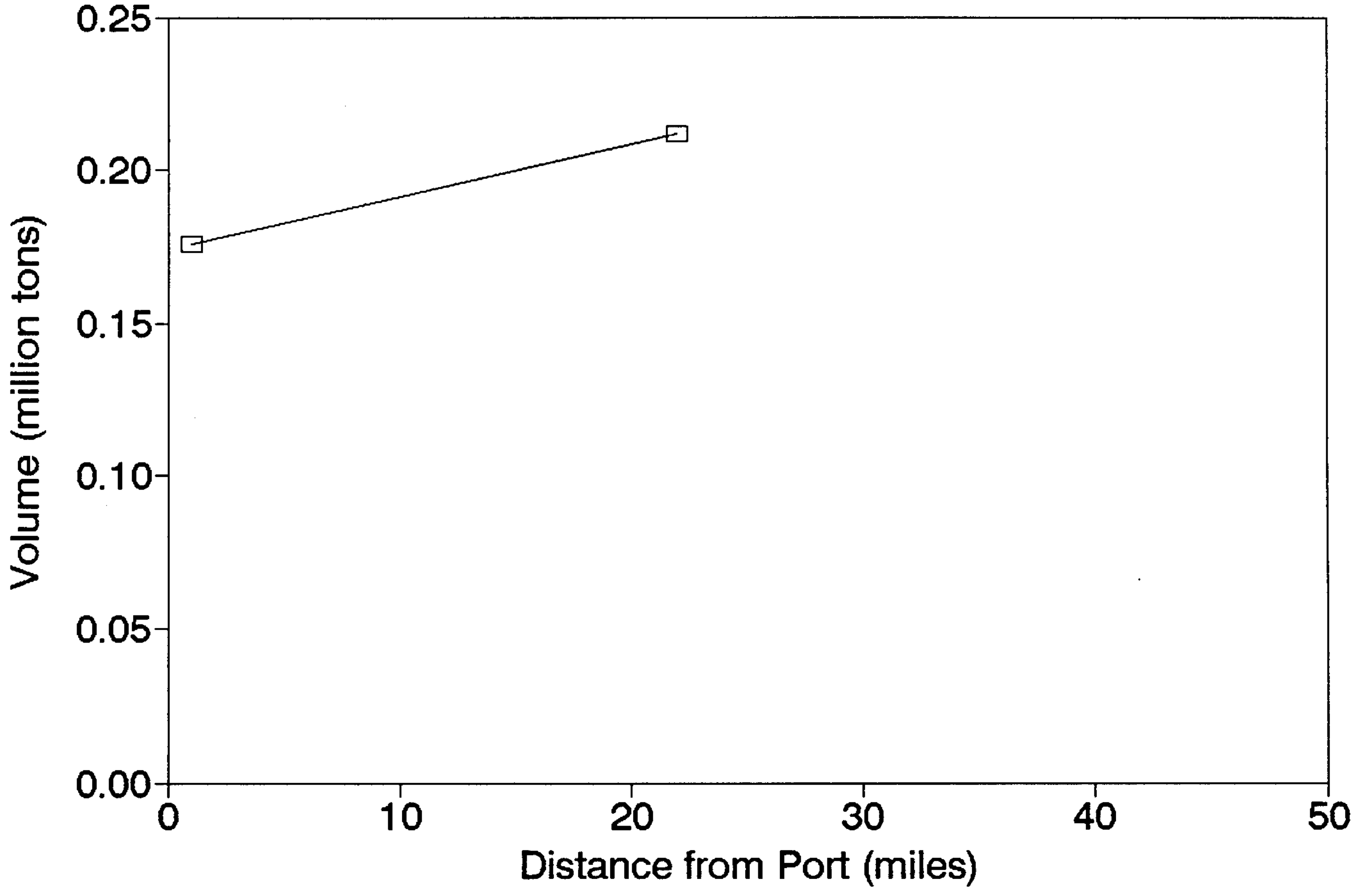


Figure 15. Cumulative Ash Volume by Distance from Port of Seattle

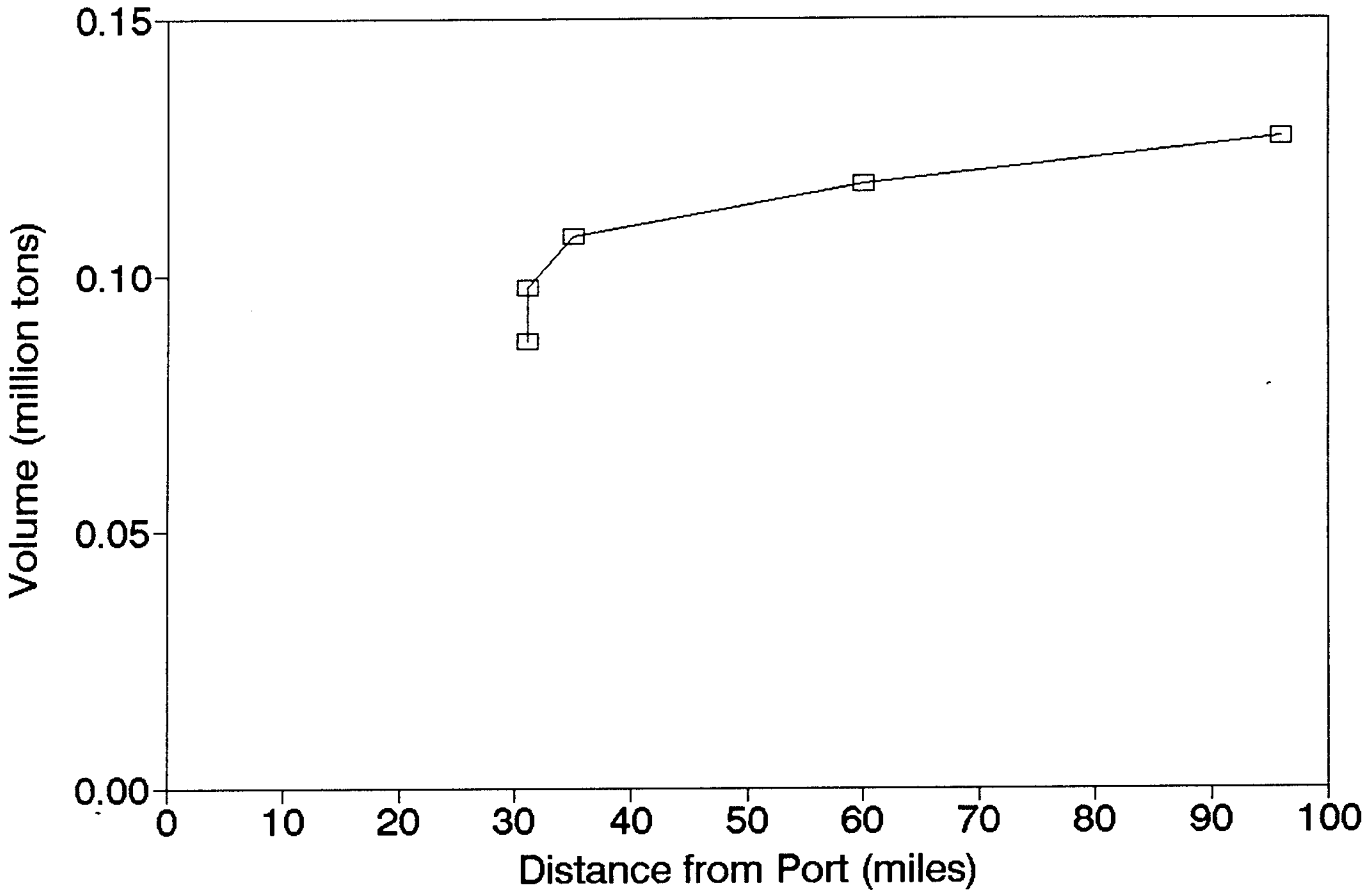


Table 5. Waste Volumes within 50 Mile Radius (million tons)

Ports	Sludge	Combined Ash	Total
New York	1.584	1.257	2.841
Miami	0.397	0.698	1.095
Galveston	0.336	0.000	0.336
Long Beach	1.299	0.212	1.511
Seattle	0.295	0.114	0.409
Ports	Sludge	Fly Ash	Total
New York	1.584	0.251	1.835
Miami	0.397	0.140	0.537
Galveston	0.336	0.000	0.336
Long Beach	1.299	0.042	1.341
Seattle	0.295	0.023	0.318

Table 6. Waste Volumes within 100 Mile Radius (million tons)

Ports	Sludge	Combined Ash	Total
New York	2.585	2.230	4.815
Miami	0.443	0.782	1.225
Galveston	0.445	0.000	0.445
Long Beach	1.742	0.212	1.954
Seattle	0.365	0.127	0.492
Ports	**Sludge**	**Fly Ash**	**Total**
New York	2.585	0.446	3.031
Miami	0.443	0.156	0.599
Galveston	0.445	0.000	0.445
Long Beach	1.742	0.042	1.784
Seattle	0.365	0.025	0.390

for the purpose of this study, more detailed analyses on waste volumes should be performed when developing a waste management plan for a specific region. The sludge volume in New York City estimated by our method is very close to that reported by the New York City Department of Environmental Protection (NYC DEP 1994). However, the sludge volume in New Jersey as reported by the New Jersey Department of Environmental Protection and Energy (NJ DEPE 1993) is higher than that derived from our population-based estimates. Population is increasing at various rates in different regions, and long term waste volume projections should take this and other factors into consideration.

Although contaminated dredged material is included in the NRL study, we have not been able to develop useful volume estimates for this waste stream within the scope of the present study. There are several data sources that are potentially useful for developing such estimates. For example, the U.S. Army Corps of Engineers Waterways Experiment Station has an electronic Bulletin Board System (BBS) for the exchange of information on contaminated sediment and dredged material. One of its on-line databases is the Ocean Disposal Database (ODD), which contains data on sediments disposed of in the ocean from all Corps of Engineers federal and permitted dredging projects. These data include location dredged, disposal site information, dates, disposal volumes, and summary chemical information for each project from 1976 to 1991 (EPA 1994a). The total volume of dredged materials in different regions can be found in the WHOI (1993) report and may be updated using data from the Corps' annual report (U.S. Army Corps of Engineers 1993). Finally, EPA's Office of Science and Technology plans to develop a National Inventory of Sites with Sediment Contamination (the "Site Inventory"). The Site Inventory will include data from existing national and regional computer databases and

will eventually compile detailed state data describing contaminated sediment sites (EPA 1994b). Thus, a thorough analysis of contaminated dredged materials in different ports will become feasible and should be considered as an important extension of this study.

3. COST ASSESSMENT FOR THE ABYSSAL OCEAN OPTION

In this study, the internal cost of abyssal seafloor isolation is estimated in two parts: source to port and port to site. In the terrestrial segment, dewatered sludge (at 20 percent solid) and ash are transported by large trucks from each sludge dewatering facility or municipal solid waste incinerator to a regional port. These wastes are mixed at the port and then loaded on barges which carry them to the abyssal disposal sites. Two separate computer models written in FORTRAN are developed to model the costs of the terrestrial and marine transportation systems.

The cost estimates developed in this study are point-to-point transport costs from sludge dewatering plants or incinerators to an abyssal site. Costs of port facilities and costs associated with unloading trucks at the port, loading barges, and unloading barges at the abyssal site are included. However, waste processing costs and costs of loading facilities at individual dewatering and incineration plants are not considered.

For example, the entire sewage sludge management process consists of ten stages: (i) production, (ii) thickening, (iii) stabilization, (iv) disinfection, (v) conditioning and dewatering, (vi) storage, (vii) loading, (viii) hauling, (ix) ultimate disposal, and (x) monitoring and control. The total cost of sludge management is influenced by the location of the sewage plant, sludge characteristics (percentage solid), annual throughput, useful life of the system, and financial factors (Leschine and Broadus, 1985). In this study, the cost calculation starts at the point when stage (vii) is completed, that is, sludge has been loaded onto a truck. This assumption is also applied to ash.

Costs associated with stages prior to loading are not considered here, since they are the

same for all management alternatives. There is, however, one exception: the sludge dewatering cost. Historically, sewage sludge was transported to offshore sites (the 12-Mile and 106-Mile Sites for the New York area) at three percent solids. Current land-based sludge management technologies all require dewatering to about 20 percent. In New York City, sludge is currently dewatered to 28 percent solid at a cost of close to $200 per dry ton (NYC DEP 1994). The cost of dewatering is positively correlated with percentage solid. Higher percentage solid means a smaller total sludge volume to be transported, and thus lower transport cost. A more formal analysis should address these trade-offs (see NRC 1984). Based on current practice in most regions, we assume that sludge is dewatered to 20 percent solid. All costs are in 1994 dollars.

3.1. Source to Port Cost

Dewatered sludge and ash can be shipped by truck, railroad and barge. Liquid sludge can also be transported by pipeline. An early EPA (1977) study concluded that rail had a low-cost advantage over other options, especially for long-distance hauling, and that pipelines were least expensive for large volumes of liquid sludge. In this study, we examine only the cost of transporting dewatered sludge and ash by truck. We regard this as the baseline cost for the terrestrial segment, because trucks can be used in all regions. Other modes of transportation may provide low-cost advantages in certain places. In that case, the cost of trucking will represent a conservative estimate.

As noted, the source to port cost is the point-to-point cost; the cost of loading facilities at sludge dewatering plants and incinerators is not included. The cost associated with unloading operations is included in the cost of port facilities in the marine segment. Each plant is assumed

to be a management unit. Trucks shuttle between the plant and the port. The number of trucks required is determined by plant output and transportation distance. The waste transport problem may be optimized for a region using a collection and truck routing model (Gottinger 1991). This optimization is not included in our study.

We develop a computer model to estimate the transportation cost of dewatered sludge and ash from source to port. The model is based on the general algorithm outlined in EPA (1977). The input variables are summarized in Table 7. The cost estimation proceeds as follows.

For a given size of sludge dewatering plant or incineration plant, the total number of trips from the plant to port (*TRIP*) can be calculated as

$$TRIP = \frac{VOLUME}{CAPACITY} \tag{1}$$

where *VOLUME* is the total annual volume of waste output from the plant, and *CAPACITY* is the capacity of one truck. *TRIP* always takes the next highest integer. For sludge, *VOLUME* is measured in cubic yards. Truck *CAPACITY* is 30 cubic yards. Sludge is lighter than ash; its density is 64.38 pounds per cubic foot at 20 percent solid, versus 127.5 pounds per cubic foot for ash at 85 percent solid. A full truck load of sludge (30 cubic yards) is 23.7 metric tons. Because of road and vehicle limitations, we assume that the load limit for ash is 23.7 tons rather than 30 cubic yards. Thus, *VOLUME* is measured in tons for ash.

The total annual truck usage (*USE*) is

$$USE = 2 * DISTANCE * TRIP \tag{2}$$

where *DISTANCE* is one-way distance from the plant to the port. *USE* measures the total milage of all trips by all trucks in a year, and *TRIP* is defined in (1). The total fuel consumption in a

Table 7. Summary of Input Variables, Terrestrial Model

INPUT VARIABLES	DESCRIPTION	VALUE	UNIT
VOLUME	Annual sludge volume	1,000 - 200,000	cubic yard
DISTANCE	One way distance	1 - 100	miles
CAPACITY	Truck capacity	30	cubic yard
MPG	Fuel use	4.0	miles per gallon
DISTL	Distance on local roads	20	miles
SPEEDH	Average high speed	35	miles per hour
SPEEDL	Average low speed	25	miles per hour
LOAD	Load time	30	minutes
UNLOAD	Unload time	15	minutes
DAYS	Operation days per year	360	days
HOURS	Operation hours per day	8	hours
MAINTE	Average maintenance time per day	2	hours
FCOST	Unit fuel cost	1.3	$ per gallon
OPERCOST	Truck operation cost	0.6	$ per mile
LCOST	Driver wages and benefits	16	$ per man-hour
ADFACTOR	Adjustment factor for overhead	1.25	-
TKCOST	Truck capital cost	112,500	$ per truck
RESIDUAL	Factor for estimating truck residual value	0.15	-
AMPERIOD	Amortization period	6	years
DISCOUNT	Discount rate	7.25	percent

year is

$$FUEL = \frac{USE}{MPG} \tag{3}$$

where *MPG* is the fuel use in miles per gallon, and *USE* is defined in (2).

Since one truck can transport a larger volume of waste by making multiple trips in a day if the distance is short enough, the number of trucks needed for a given volume is affected by the distance. To estimate the number of trucks needed for the sludge volume, we first estimate the time for a round-trip (*TRIPHOUR*):

$$TRIPHOUR = 2*[\frac{DISTANCE-DISTL}{SPEEDH} + \frac{DISTL}{SPEEDL}] + \frac{LOAD}{60} + \frac{UNLOAD}{60} \tag{4}$$

where *DISTL* is the distance travelled on local roads, *SPEEDL* is the average speed on local roads, and *SPEEDH* is the average speed of trucks on highways. The round-trip time is extended by adding the time for loading (*LOAD*) and unloading (*UNLOAD*) sludge (all in minutes).

The total number of trips a truck can make in a year can be estimated as

$$TKTRIP = \frac{DAYS*(HOURS-MAINTE)}{TRIPHOUR} \tag{5}$$

where *DAYS* is the number of days per year the truck is in operation, *HOURS* is the number of hours per day the transportation system is operational, *MAINTE* is the number of hours per day used for truck maintenance, and *TRIPHOUR* is defined in (4). *TKTRIP* is an integer.

Thus, the number of trucks required for the system is

$$TRUCK = \frac{TRIP}{TKTRIP} \qquad (6)$$

where *TRIP* and *TKTRIP* are defined in (1) and (5), respectively. In actual computation, *TRUCK* always takes the next highest integer.

The total man-hours per year (*MANHOUR*) can be calculated as

$$MANHOUR = 1.1*TRIPHOUR*TRIP \qquad (7)$$

where TRIPHOUR and TRIP are defined in (4) and (1), respectively. The total man-hours is the total operation hours of all trucks in a year plus a 10 percent contingency factor.

The total fuel cost (*FUELCOST*) per year is

$$FUELCOST = FUEL*FCOST \qquad (8)$$

where *FCOST* is the unit fuel cost, and *FUEL* is defined in (3). Similarly, the annual truck maintenance cost for the system is

$$MAINCOST = USE*OPERCOST \qquad (9)$$

where *OPERCOST* is the truck maintenance cost per mile, and *USE* is defined in (2). Also, the annual cost of truck drivers can be estimated as

$$DRIVCOST = MANHOUR*LCOST \qquad (10)$$

where *LCOST* is the labor cost per hour (wages and benefits), and *MANHOUR* is defined in (7).

Thus, the total annual truck operation and maintenance cost (*TOCOST*) is the sum of the costs of fuel, maintenance and labor, with an upward adjustment (*ADFACTOR*, 25 percent) to account for overhead costs.

$$TOCOST = ADFACTOR*(FUELCOST+MAINCOST+DRIVCOST) \tag{11}$$

The capital cost of each truck is amortized. The residual value of the truck is assumed to be

$$RESVALUE = RESIDUAL*TKCOST \tag{12}$$

where *RESIDUAL* is the factor calculating the residual value, and *TKCOST* is the capital cost of the truck.

The standard amortization factor (*AMFACTOR*) is

$$AMFACTOR = \frac{0.01*DISCOUNT}{1-\left(\frac{1}{1+0.01*DISCOUNT}\right)^{AMPERIOD}} \tag{13}$$

where *DISCOUNT* is the discount rate, and *AMPERIOD* is the amortization period.

The annual truck capital cost (*TTKCOST*) is then

$$TTKCOST = TRUCK*[(TKCOST-RESVALUE)*AMFACTOR+ 0.01*RESVALUE*DISCOUNT] \tag{14}$$

where *TRUCK* and *RESVALUE* are defined in (6) and (12), respectively.

Finally, the total annual cost of the transportation system (*TOTCOST*) is the sum of the total operating cost (11) and total capital cost (14)

$$TOTCOST = TOCOST+TTKCOST \tag{15}$$

Then, the unit cost of transporting dewatered sludge or ash can be easily calculated as

$$UNITCOST = \frac{TOTCOST}{VOLUME} \tag{16}$$

As noted, *UNITCOST* is in dollars per cubic yard for sludge and dollars per ton for ash. The unit cost for sludge can also be calculated in dollars per metric ton (*COSTPMT*) as

$$COSTPMT = \frac{1000*TOTCOST}{0.454*27*VOLUME*DENSITY} \tag{17}$$

where density is 64.38 pound per cubic foot for sludge at 20 percent solid.

The computer program implementing these calculations in FORTRAN is shown in Appendix 2. We performed simulations using the input data summarized in Table 7. The results are illustrated in Figures 16 through 20.

Figure 16 shows the total source-to-port cost of transporting various volumes of dewatered sewage sludge. The one-way distance is fixed at 80 miles and the annual sludge volume varies from 1,000 to 150,000 cubic yards, or 790 to 118,000 metric tons. The upper end is 324 tons per day, which exceeds the output of most dewatering facilities (EPA 1989) and the ash throughput of small to medium sized incinerators (see Tables 3 and 4 for combined ash volumes). If only fly ash (20 percent of the total) is transported, then the volume range also covers large incinerators.

The unit cost of transportation and the number of trucks required as a function of waste volume in metric tons are depicted in Figure 17. The one-way distance is again fixed at 80 miles. As the waste volume rises, the number of trucks increases from one to 14 and the unit transport cost approaches \$15.6 per ton.

Total annual and unit costs of transportation as a function of distance are plotted in

Figure 16. Total Annual Transport Cost
Source to Port (80 miles)

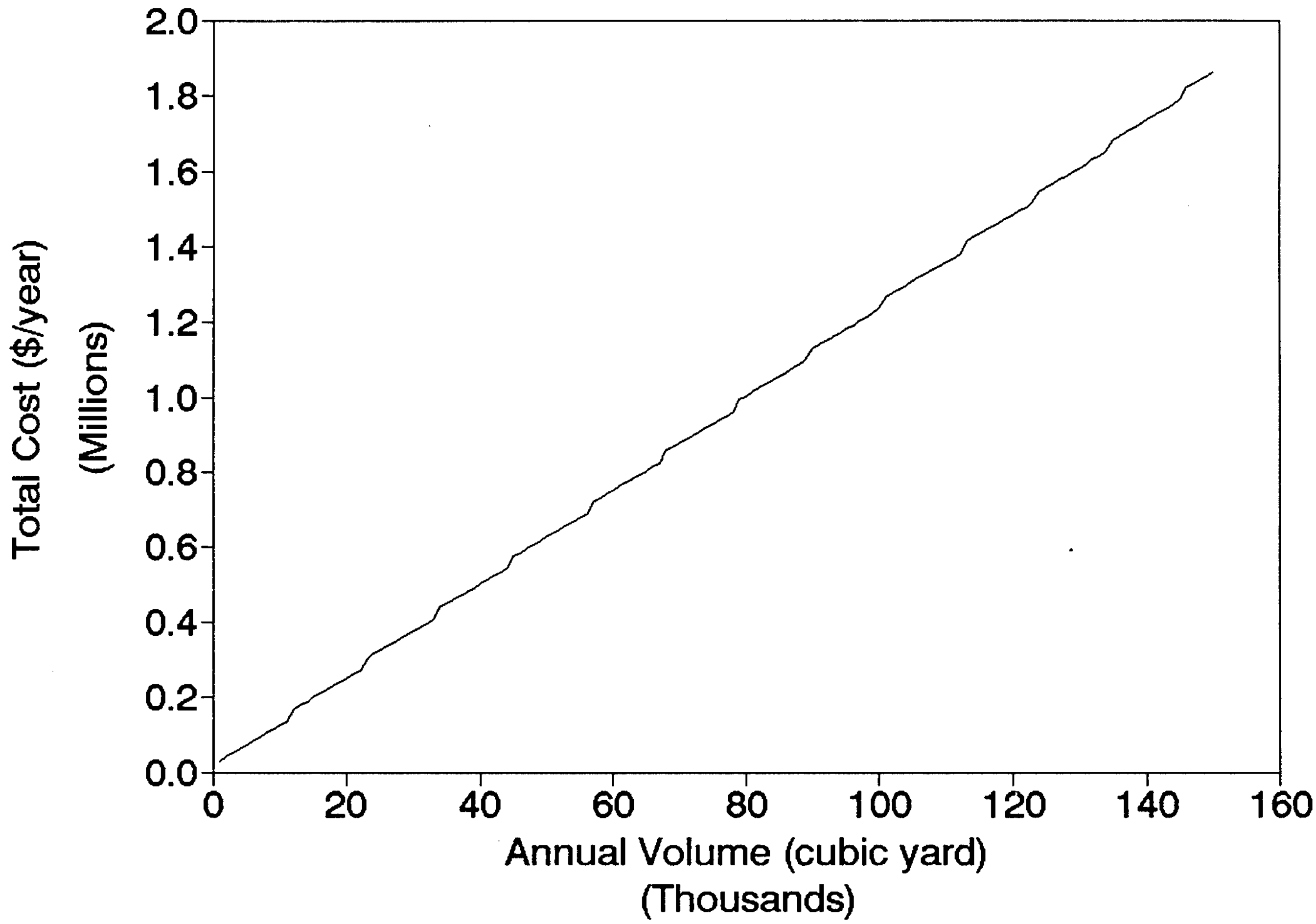


Figure 17. Unit Transport Cost
Source to Port (80 miles)

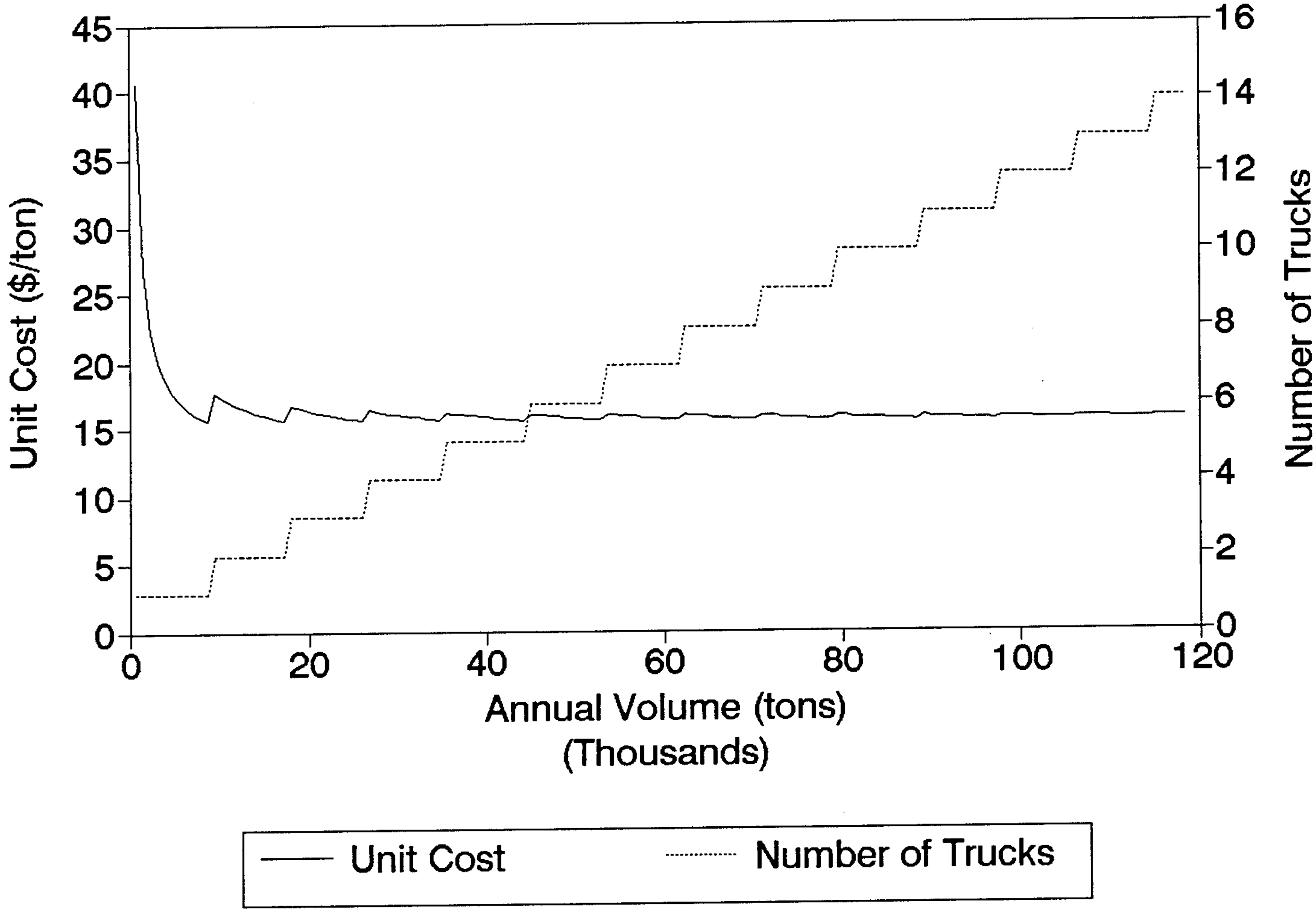


Figure 18. Total Annual Transport Cost Source to Port (150,000 cubic yard)

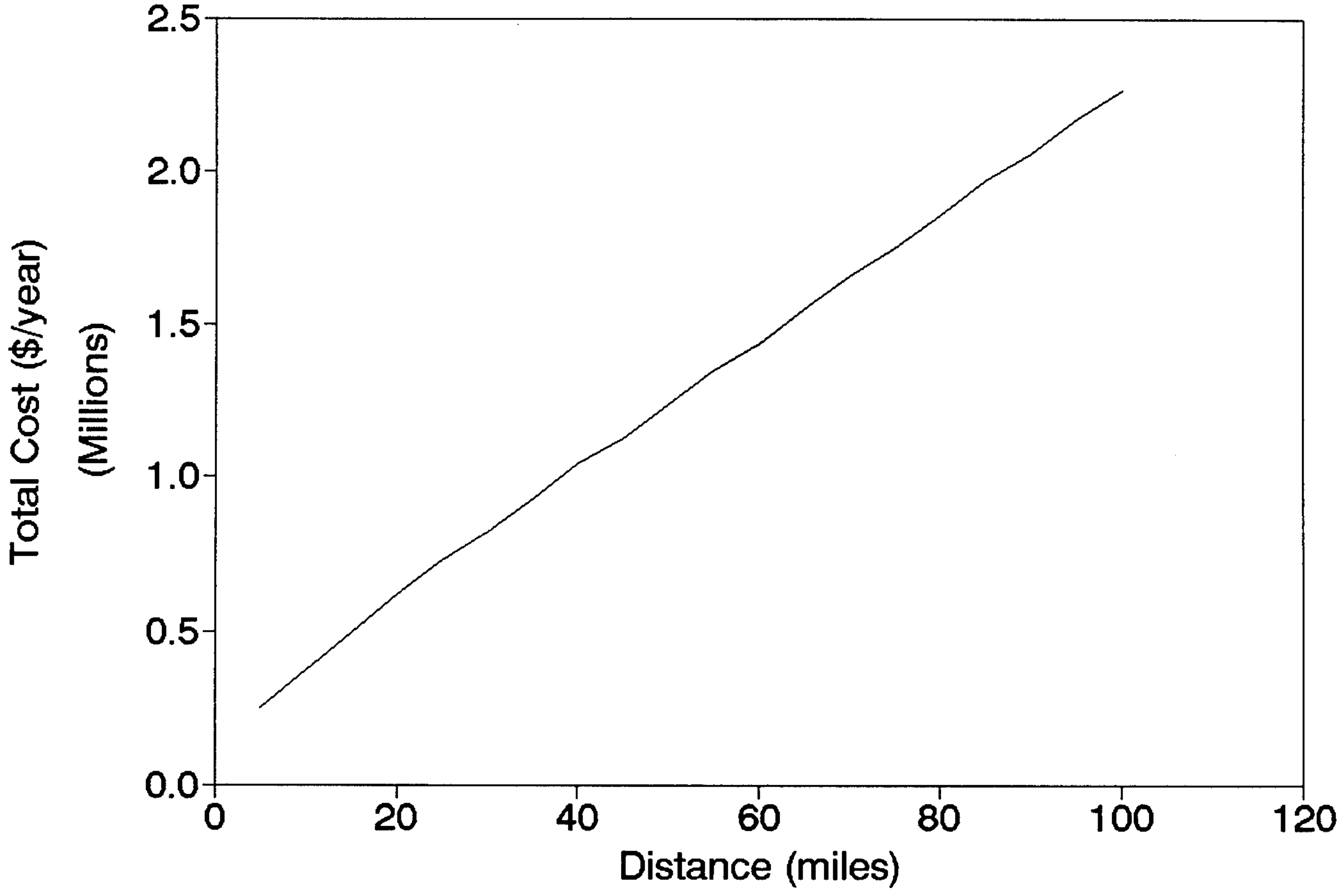


Figure 19. Unit Transport Cost
Source to Port (150,000 cubic yard)

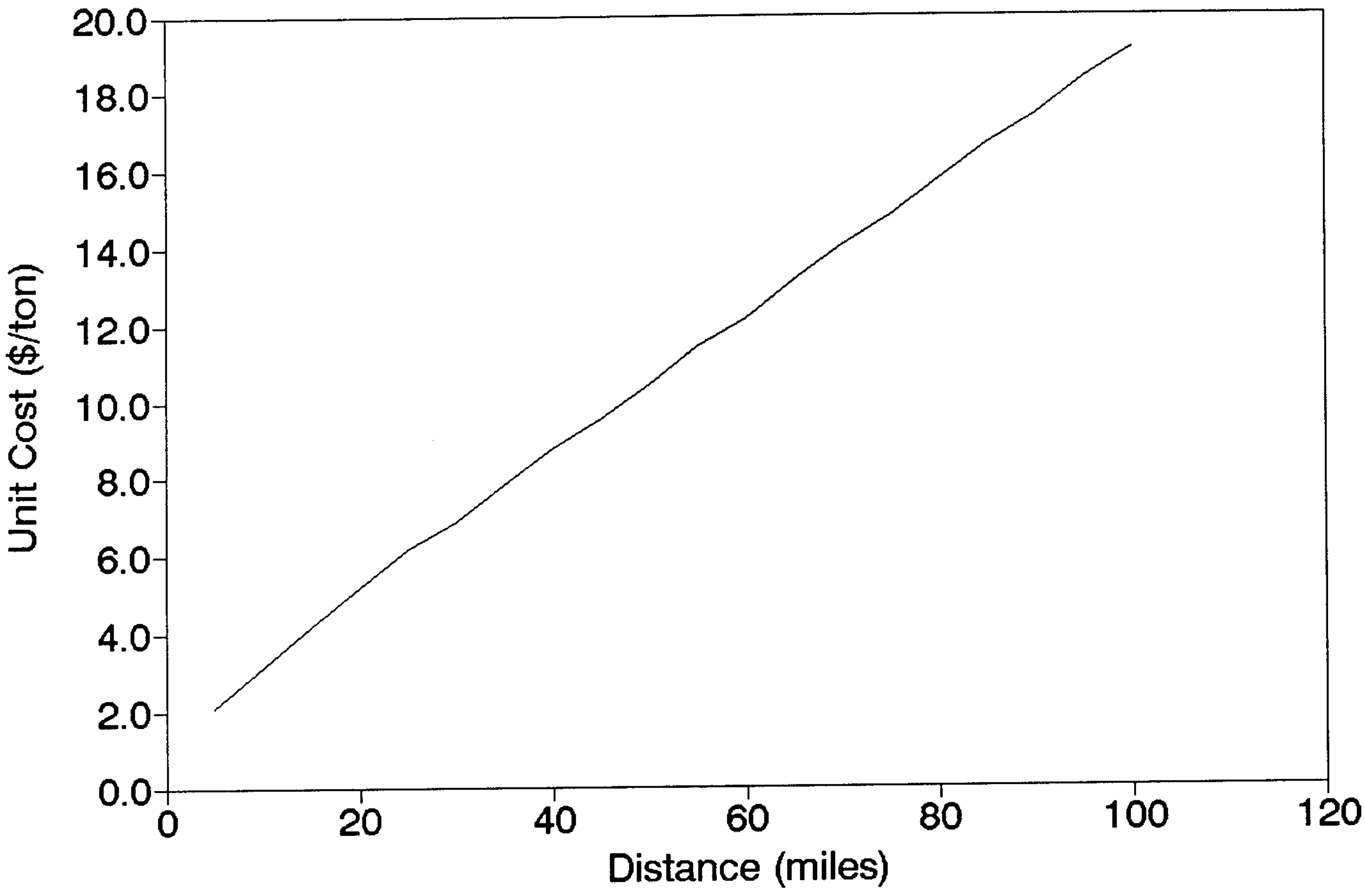
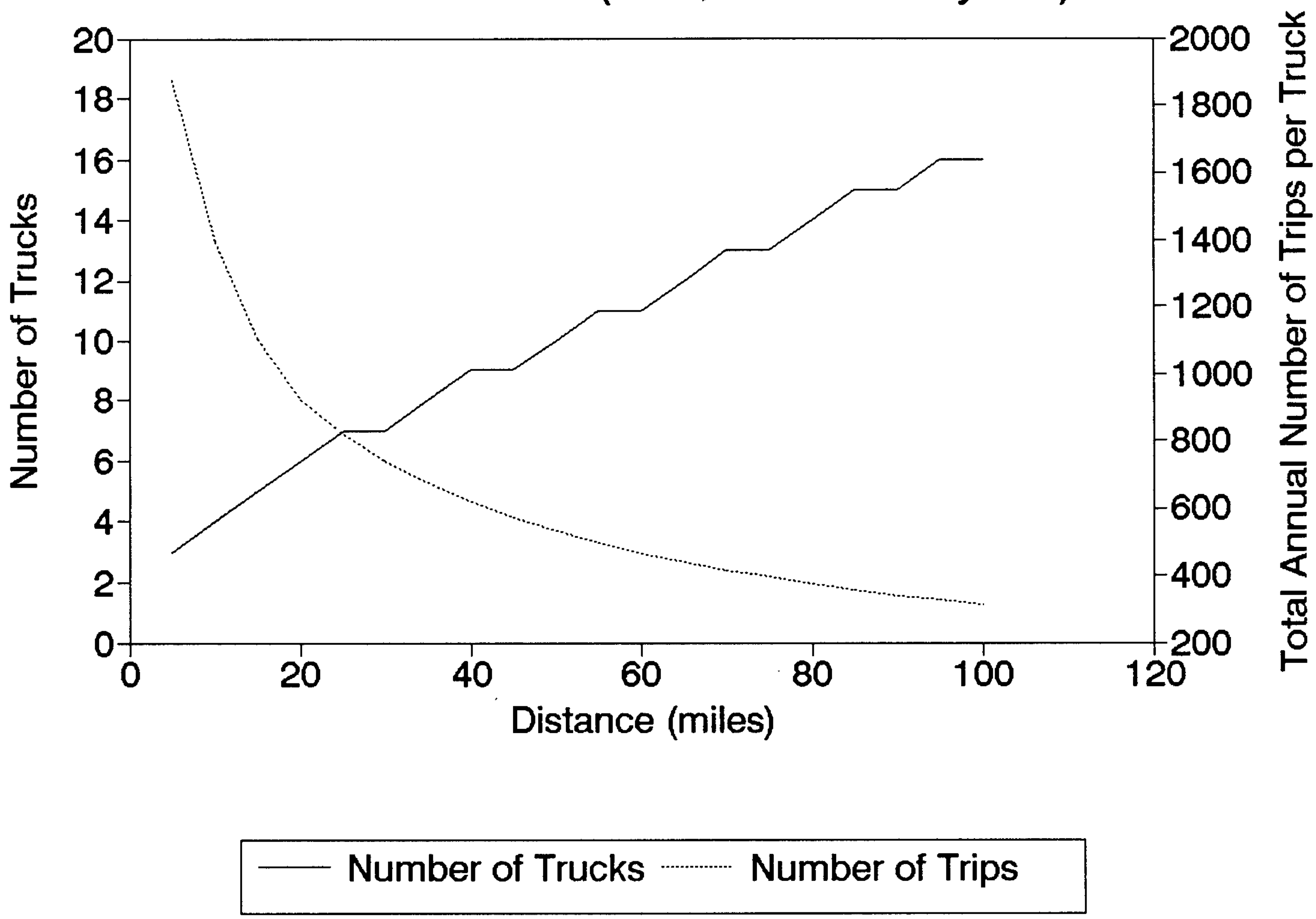


Figure 20. System Requirement
Source to Port (150,000 cubic yard)



Figures 18 and 19, respectively. The one-way distance varies from 5 to 100 miles. The waste volume is fixed at 150,000 cubic yards for sludge, or 118,000 metric tons. As shown in Figure 19, at this volume, the unit transport cost is $2.10, $10.47 and $19.10 per ton when the distance is 5, 50, and 100 miles, respectively.

Figure 20 further illustrates the truck fleet requirement as distance varies. For an annual waste volume of 118,000 metric tons, the number of trucks required rises from one at 5 miles to 16 at 100 miles. This is because the maximum number of round trips a truck can make in a year decreases from 1,879 at 5 miles to 313 at 100 miles.

It should be pointed out that the 30 cubic yard dump truck used in this study is a large truck. Should smaller trucks be used, the costs would be higher. For example, an earlier study concluded that if 15 cubic yard trucks were used, the unit cost would be up to 60 percent higher (EPA 1978). This is also a subject for further study.

3.2. Port to Site Cost

As noted, sludge and ash are transported to a port, then mixed and loaded onto a barge. The barge carries the waste to a designated abyssal isolation site and delivers it to the seafloor before returning to port for the next load. The cost of port to site transportation includes capital and operating costs of port facilities and vessel systems. The port facilities and marine systems concepts for this study have been developed by Oceaneering Technologies. Four conceptual designs are examined separately:

- Surface Emplacement, including one special barge, one tug and one set of port facilities;

- ROV Glider, including one launcher/glider, one tug and one set of port facilities;
- Direct Descent Disc, including five disc/floaters, one tug and one set of port facilities, and
- Pipe Riser, including one pipe riser, one supply barge, one tug and one set of port facilities.

We define each of the four conceptual designs as a *vessel* system. The marine waste transportation *fleet* for a port may have more than one vessel systems. The fleet capacity depends on the waste throughput in the port (see Tables 5 and 6). It is possible to optimize the vessel system configuration. For example, two supply barge/tugs may share one set of port facilities and one pipe riser. When the transport distance is short, two barges may even share one tug (this is not likely for abyssal sites). In this study, facility sharing is not considered. Many technologies in these systems are new, and it is appropriate to be conservative in our cost estimates of these systems.

The cost estimation procedure is designed specifically for the four design concepts. Input variables are summarized in Table 8. For a given volume of waste materials in a region, the total number of trips from port to site (*TRIPP*) can be calculated as

$$TRIPP = \frac{VOLUMEP}{CAPV} \tag{18}$$

where *VOLUMEP* is the total annual waste volume from the port, and *CAPV* is the capacity of one vessel. *TRIPP* always takes the next integer.

The total annual usage of vessels (*USEV*) is

Table 8. Summary of Input Variables, Marine Model

INPUT VARIABLES	DESCRIPTION	VALUE	UNIT
VOLUMEP	Annual throughput at the port	100,000 - 6,000,000	metric tons
DISTP	One way distance	267 - 1,045	nautical miles
CAPV	Vessel capacity	25,000	dwt
SPEED	Average speed	15	knots
LOADV	Load time	5.2	hours
UNLOADV	Unload time	2-12	hours
DOWNTIME	Average down time per trip	8	hours
DAYS	Operation days per year	248-329	days
HOURS	Operation hours per day	24	hours
VFCOST	Diesel fuel cost per nautical mile	40	$ per n. mile
VLCOST	Lube oil cost per nautical mile	0.5	$ per n. mile
CREW	Number of crew on duty	9	persons
PERSON	Number of persons on duty in port	6	persons
VMLCOST	Crew wages	55	$ per man-hour
VPLCOST	Port labor wages	45	$ per man-hour
CONSUMCT	Cost of consumables per trip	2700 - 142,090	$ per trip
MCOST	Other annual operating cost	2.32 - 4.64	$\$10^6$ per year
APFACTOR	Adjustment factor for overhead	1.20	-
VCOST	Capital cost	94.83 - 154.87	$\$10^6$ per unit
ACFACTOR	Adjustment factor for capital cost	1 - 3	-
AMPERIOD	Amortization period	8	years
DISCOUNT	Discount rate	7.25	percent

$$USEV = 2*DISTP*TRIPP \tag{19}$$

where *DISTP* is one-way distance from port to site. *USEV* measures the total nautical miles of all trips by all vessels in a year, and *TRIPP* is defined in (18).

Since one vessel can transport a larger volume of waste by making more trips in a year if the distance is short, the number of vessels needed for a given volume is affected by the distance. To estimate the number of vessels needed for the waste volume, we first estimate the time for a round-trip (*TRIPHV*):

$$TRIPHV = 2*\frac{DISTP}{SPEED}+LOADV+UNLOADV+DOWNTIME \tag{20}$$

where *SPEED* is the average speed of the vessel. The round-trip time is extended by adding the time for loading (*LOADV*), unloading (*UNLOADV*), and average down time for various reasons (*DOWNTIME*).

The total number of trips a vessel can make in a year can be estimated as

$$VTRIP = \frac{DAYS*HOURS}{TRIPHV} \tag{21}$$

where *DAYS* is the number of days per year when the vessel is in operation, *HOURS* is the number of hours per day the transportation system is operational, and *TRIPHV* is defined in (20). *VTRIP* is an integer.

Thus, the number of vessels required for the system is

$$VESSEL = \frac{TRIPP}{VTRIP} \tag{22}$$

where *TRIPP* and *VTRIP* are defined in (18) and (21), respectively. In actual computation,

VESSEL always takes the next integer.

The total fuel cost (*FUELCV*) per year is

$$FUELCV = USEV * VFCOST \tag{23}$$

where *VFCOST* is the unit fuel cost per mile, and *USEV* is defined in (19).

The total cost of lube oil (*LUBECV*) per year is

$$LUBECV = USEV * VLCOST \tag{24}$$

where *VLCOST* is the unit cost of lube oil per mile, and *USEV* is defined in (19).

The total man-hours per year for the marine crew (*MANHOURV*) can be calculated as

$$MANHOURV = 1.1 * CREW * TRIPHV * TRIPP \tag{25}$$

where *CREW* is the number of crew on duty, and *TRIPHV* and *TRIPP* are defined in (20) and (18), respectively. The total man-hours is the total operation hours of all vessels in a year with a 10 percent increase for contingencies.

The total man-hours per year for persons attending port facilities (*MANHOURP*) is

$$MANHOURP = 1.1 * 365 * 24 * PERSON * VESSEL \tag{26}$$

where *PERSON* is the number of persons in a shift attending the port facilities. It is assumed that the facilities are in operation 24 hours a day throughout the year.

The annual labor cost for marine crew can be estimated as

$$CREWCOST = MANHOURV * VMLCOST \tag{27}$$

where *VMLCOST* is the marine labor cost per hour (wages and benefits), and *MANHOURV* is defined in (25).

The annual labor cost for port personnel can be estimated as

$$PORTLC = MANHOURP*VPLCOST \tag{28}$$

where *VPLCOST* is the port labor cost per hour (wages and benefits), and *MANHOURP* is defined in (26).

The annual cost of consumables including stores, Geotextile bags and transponders (*CONSUMC*) is

$$CONSUMC = TRIPP*CONSUMCT \tag{29}$$

where *CONSUMCT* is the cost of consumables per trip and *TRIPP* is defined in (18).

The total annual vessel operation and maintenance cost, including port costs, (*VTOCOST*) is:

$$\begin{aligned} VTOCOST = APFACTOR*(&FUELCV+LUBECV+CREWCOST+PORTLC+ \\ &CONSUMC+VESSEL*MCOST) \end{aligned} \tag{30}$$

where *MCOST* is the total annual miscellaneous cost per vessel, including maintenance/spares, docking fees, and insurance (for the pipe riser, it also includes the cost of diesel fuel and lube oil for a generator, thrusters and pumps at the riser buoy). *APFACTOR* is the adjustment factor to account for overhead costs of the marine system.

The standard amortization factor (*AMFACTOR*) is

$$AMFACTOR = \frac{0.01*DISCOUNT}{1-\left(\frac{1}{1+0.01*DISCOUNT}\right)^{AMPERIOD}} \tag{31}$$

where *DISCOUNT* is the discount rate, and *AMPERIOD* is the amortization period.

The annual vessel system capital cost (*TVCOST*) is then

$$TVCOST = VESSEL*VCOST*ACFACTOR*AMFACTOR \tag{32}$$

where *VCOST* is the capital cost of a vessel including *all* related port and marine facilities, *ACFACTOR* is the adjustment factor for system capital cost, and *VESSEL* is defined in (22).

Finally, the total annual cost of the vessel transportation system (*TOTPCOST*) is the sum of the total operating cost (30) and total capital cost (32)

$$TOTPCOST = VTOCOST+TVCOST \tag{33}$$

Then, the unit cost can be easily calculated as

$$UPCOST = \frac{TOTPCOST}{VOLUMEP} \tag{34}$$

A FORTRAN computer program implementing the above algorithm is shown in Appendix 3. We performed simulations using the inputs in Table 8 and data in Tables 9 to 14. Most engineering and cost data for these simulations were provided by Oceaneering Technologies. The design vessel capacity for all four concepts is 25,000 dwt. Vessel speed is 15 knots. Table 9 presents distances between each of the five ports considered and their corresponding abyssal sites. Loading time is the same (5.2 hours) for the four technologies; their different unloading times are summarized in Table 10. All vessels are designed for seastate five. Corresponding operational days at different abyssal sites are included in Table 11. Vessel capital costs, costs of consumables per trip and other annual operating costs for the four concepts are presented in Tables 12, 13 and 14, respectively. As shown in Table 13, three of the four technologies employ plastic (Geotextile) bags. Mixed sludge and ash are loaded into bags at port, and the bags are carried to abyssal sites. The bags are released at the surface in the case of Surface

Table 9. Port to Site Transit Distance (in nautical miles)

Ports	Atlantic 1 28°N 70°W	Atlantic 2 27°N 61°W	Gulf 25°N 93.5°W	Pacific 1 33.5°N 124°W	Pacific 2 35°N 134°W
New York	787.3	1044.7	-	-	-
Miami	560.6	1032.5	-	-	-
Galveston	-	-	267.2	-	-
Los Angeles	-	-	-	286.6	782.1
Seattle	-	-	-	851.2	920.2

Table 10. Emplacement (Unloading) Time

Technologies	Hours
Surface Emplacement	2
ROV Glider	6
Direct Descent Disc	10
Pipe Riser	12

Table 11. Abyssal Site Operational Availability

Sites	Days per Year (Seastate 5)
Atlantic 1 (28°N, 70°W)	325
Atlantic 2 (27°N, 61°W)	307
Gulf (25°N, 93.5°W)	329
Pacific 1 (33.5°N, 124°W)	266
Pacific 2 (35°N, 134°W)	248

Table 12. Vessel Capital Cost ($ million)

Technologies	Concept	Port Facilities	Tug	Barge	Total Vessel Cost
Surface Emplacement	45.21	17.71	31.91	-	94.83
ROV Glider	86.68	17.71	31.91	-	136.30
Direct Descent Disc	105.25	17.71	31.91	-	154.87
Pipe Riser	50.30	17.71	31.91	41.91	141.83

Table 13. Cost of Consumables per Trip ($)

Technologies	Stores	Geotextile Bags	Transponders	Total Cost per Trip
Surface Emplacement	2700	60333	9000	72033
ROV Glider	2700	86292	1000	89992
Direct Descent Disc	2700	136890	2500	142090
Pipe Riser	2700	-	-	2700

Table 14. Other Annual Operating Cost ($ million)

Technologies	Concept	Port Facilities	Tug	Barge	Total Vessel Cost
Surface Emplacement	1.39	0.18	0.75	-	2.32
ROV Glider	2.54	0.18	0.75	-	3.47
Direct Descent Disc	2.99	0.18	0.75	-	3.92
Pipe Riser	2.40	0.18	0.75	1.31	4.64

Emplacement, carried by gliders to abyssal depth and then released 200 meters above bottom by ROV Glider, or delivered to abyssal depth by disks and released 90 meters above bottom by the Direct Descent Disk. All bags are expendable. With the Pipe Riser, waste is delivered to the site through a pipe linking surface and seafloor (no bags are used).

Using waste volume estimates summarized in Tables 5 and 6, we calculate the total and unit costs for the marine segments between the five ports and their abyssal sites, such as New York to Atlantic 1 and New York to Atlantic 2. Other combinations are shown in Table 9. The calculations are performed for four scenarios: (i) transporting sludge and combined ash from within a 50 mile radius, (ii) transporting sludge and fly ash only from within a 50 mile radius, (iii) transporting sludge and combined ash from within a 100 mile radius, and (iv) transporting sludge and fly ash only from within a 100 mile radius.

The results for the four scenarios are reported in Tables 15 through 18. These results indicate that unit cost is strongly affected by vessel system utilization. Higher regional waste volumes are associated with lower unit costs. For example, in the port of New York, the waste volume within 50 miles is 2.8 million tons if both sludge and combined ash are transported (Table 5). The unit cost associated with using Surface Emplacement at Atlantic 1 is $25.14 per ton (Table 15). If we only consider fly ash and sludge, the waste volume reduces to 1.8 million tons (Table 5), and the unit cost for this combination of site and technology increases to $33.65 per ton. When the study region has a 100 mile radius, the waste volume is 4.8 million tons with combined ash and 3.0 million tons with fly ash (Table 6). The unit costs are $23.35 per ton and $24.20 per ton, respectively, for the same disposal site.

Because vessel capacity is fixed at 25,000 dwt (Table 8), the unit cost is very high for

Table 15. Summary of Marine Model Results: Sludge and Combined Ash within 50 Miles

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
1	1	1	2.8	787	65	2	71.41	25.14
1	1	2	2.8	787	63	2	90.95	32.01
1	1	3	2.8	787	61	2	105.74	37.22
1	1	4	2.8	787	60	2	84.13	29.61
1	2	1	2.8	1045	48	3	98.76	34.76
1	2	2	2.8	1045	47	3	126.69	44.59
1	2	3	2.8	1045	46	3	145.16	51.09
1	2	4	2.8	1045	45	3	122.22	43.02
2	1	1	1.1	561	87	1	30.73	28.06
2	1	2	1.1	561	84	1	40.18	36.70
2	1	3	1.1	561	80	1	46.73	42.68
2	1	4	1.1	561	79	1	38.09	34.78
2	2	1	1.1	1033	49	1	34.56	31.56
2	2	2	1.1	1033	47	1	44.01	40.19
2	2	3	1.1	1033	46	1	50.56	46.17
2	2	4	1.1	1033	46	1	41.91	38.28
3	3	1	0.3	267	156	1	23.98	71.37
3	3	2	0.3	267	145	1	32.71	97.35
3	3	3	0.3	267	135	1	37.30	111.02
3	3	4	0.3	267	130	1	33.64	100.11

Table 15. Summary of Marine Model Results: Sludge and Combined Ash within 50 Miles (Continued)

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
4	4	1	1.5	287	120	1	31.04	20.54
4	4	2	1.5	287	112	1	40.91	27.07
4	4	3	1.5	287	104	1	48.56	32.14
4	4	4	1.5	287	101	1	37.10	24.55
4	5	1	1.5	782	50	2	58.55	38.75
4	5	2	1.5	782	49	2	76.81	50.84
4	5	3	1.5	782	47	2	88.15	58.34
4	5	4	1.5	782	46	2	75.34	49.86
5	4	1	0.4	851	50	1	26.25	64.17
5	4	2	0.4	851	49	1	35.05	85.70
5	4	3	0.4	851	47	1	39.84	97.40
5	4	4	0.4	851	47	1	35.67	87.22
5	5	1	0.4	920	44	1	26.46	64.70
5	5	2	0.4	920	42	1	35.27	86.23
5	5	3	0.4	920	41	1	40.05	97.93
5	5	4	0.4	920	41	1	35.89	87.75

Notes:

Port: 1 = New York, 2 = Miami, 3 = Galveston, 4 = Long Beach, 5 = Seattle.
Site: 1 = Atlantic 1, 2 = Atlantic 2, 3 = Gulf, 4 = Pacific 1, 5 = Pacific 2.
Tech: 1 = Surface Emplacement, 2 = ROV Glider, 3 = Direct Descent Disc, 4 = Pipe Riser.
Max Trip: This is the maximum number of round trips a vessel can make in a year, and is used to determine the number of vessels needed at a port. Depending on the number of vessels in the marine transportation system, the actual number of trips needed for a given waste volume is usually smaller than the maximum possible.

Table 16. Summary of Marine Model Results: Sludge and Fly Ash within 50 Miles

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
1	1	1	1.8	787	65	2	61.75	33.65
1	1	2	1.8	787	63	2	80.33	43.77
1	1	3	1.8	787	61	2	92.51	50.41
1	1	4	1.8	787	60	2	77.54	42.26
1	2	1	1.8	1045	48	2	65.26	35.57
1	2	2	1.8	1045	47	2	83.84	45.69
1	2	3	1.8	1045	46	2	96.02	52.32
1	2	4	1.8	1045	45	2	81.05	44.17
2	1	1	0.5	561	87	1	26.33	49.04
2	1	2	0.5	561	84	1	35.26	65.66
2	1	3	0.5	561	80	1	40.37	75.18
2	1	4	0.5	561	79	1	35.38	65.88
2	2	1	0.5	1033	49	1	28.25	52.60
2	2	2	0.5	1033	47	1	37.17	69.22
2	2	3	0.5	1033	46	1	42.29	78.74
2	2	4	0.5	1033	46	1	37.29	69.45
3	3	1	0.3	267	156	1	23.98	71.37
3	3	2	0.3	267	145	1	32.71	97.35
3	3	3	0.3	267	135	1	37.30	111.02
3	3	4	0.3	267	130	1	33.64	100.11

Table 16. Summary of Marine Model Results: Sludge and Fly Ash within 50 Miles (Continued)

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
4	4	1	1.3	287	120	1	30.00	22.37
4	4	2	1.3	287	112	1	39.70	29.60
4	4	3	1.3	287	104	1	46.89	34.97
4	4	4	1.3	287	101	1	36.59	27.29
4	5	1	1.3	782	50	2	56.87	42.41
4	5	2	1.3	782	49	2	74.96	55.90
4	5	3	1.3	782	47	2	85.84	64.01
4	5	4	1.3	782	46	2	74.19	55.33
5	4	1	0.3	851	50	1	25.23	79.35
5	4	2	0.3	851	49	1	33.94	106.73
5	4	3	0.3	851	47	1	38.47	120.97
5	4	4	0.3	851	47	1	34.97	109.96
5	5	1	0.3	920	44	1	25.40	79.87
5	5	2	0.3	920	42	1	34.11	107.25
5	5	3	0.3	920	41	1	38.63	121.49
5	5	4	0.3	920	41	1	35.13	110.48

Notes: See notes for Table 15.

Table 17. Summary of Marine Model Results: Sludge and Combined Ash within 100 Miles

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
1	1	1	4.8	787	65	3	112.43	23.35
1	1	2	4.8	787	63	4	172.60	35.85
1	1	3	4.8	787	61	4	199.90	41.52
1	1	4	4.8	787	60	4	162.50	33.75
1	2	1	4.8	1045	48	5	165.47	34.37
1	2	2	4.8	1045	47	5	212.10	44.05
1	2	3	4.8	1045	46	5	243.07	50.48
1	2	4	4.8	1045	45	5	204.33	42.44
2	1	1	1.2	561	87	1	31.73	25.90
2	1	2	1.2	561	84	1	41.30	33.72
2	1	3	1.2	561	80	1	48.17	39.33
2	1	4	1.2	561	79	1	38.70	31.59
2	2	1	1.2	1033	49	1	35.99	29.38
2	2	2	1.2	1033	47	2	75.90	61.96
2	2	3	1.2	1033	46	2	86.45	70.57
2	2	4	1.2	1033	46	2	75.64	61.74
3	3	1	0.4	267	156	1	24.56	55.20
3	3	2	0.4	267	145	1	33.39	75.03
3	3	3	0.4	267	135	1	38.24	85.94
3	3	4	0.4	267	130	1	33.91	76.21

Table 17. Summary of Marine Model Results: Sludge and Combined Ash within 100 Miles (Continued)

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
4	4	1	2	287	120	1	33.73	17.26
4	4	2	2	287	112	1	44.03	22.53
4	4	3	2	287	104	1	52.85	27.05
4	4	4	2	287	101	1	38.40	19.65
4	5	1	2	782	50	2	62.88	32.18
4	5	2	2	782	49	2	81.58	41.75
4	5	3	2	782	47	2	94.08	48.15
4	5	4	2	782	46	2	78.29	40.07
5	4	1	0.5	851	50	1	27.01	54.89
5	4	2	0.5	851	49	1	35.88	72.93
5	4	3	0.5	851	47	1	40.86	83.06
5	4	4	0.5	851	47	1	36.20	73.59
5	5	1	0.5	920	44	1	27.26	55.41
5	5	2	0.5	920	42	1	36.14	73.45
5	5	3	0.5	920	41	1	41.12	83.58
5	5	4	0.5	920	41	1	36.46	74.10

Notes: See notes for Table 15.

Table 18. Summary of Marine Model Results: Sludge and Fly Ash within 100 Miles

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
1	1	1	3	787	65	2	73.34	24.20
1	1	2	3	787	63	2	93.08	30.71
1	1	3	3	787	61	2	108.38	35.76
1	1	4	3	787	60	3	118.13	38.97
1	2	1	3	1045	48	3	101.07	33.35
1	2	2	3	1045	47	3	129.20	42.63
1	2	3	3	1045	46	3	148.18	48.89
1	2	4	3	1045	45	3	123.91	40.88
2	1	1	0.6	561	87	1	26.73	44.63
2	1	2	0.6	561	84	1	35.71	59.61
2	1	3	0.6	561	80	1	40.95	68.36
2	1	4	0.6	561	79	1	35.63	59.47
2	2	1	0.6	1033	49	1	28.82	48.12
2	2	2	0.6	1033	47	1	37.79	63.09
2	2	3	0.6	1033	46	1	43.04	71.85
2	2	4	0.6	1033	46	1	37.71	62.96
3	3	1	0.4	267	156	1	24.56	55.20
3	3	2	0.4	267	145	1	33.39	75.03
3	3	3	0.4	267	135	1	38.24	85.94
3	3	4	0.4	267	130	1	33.91	76.21

Table 18. Summary of Marine Model Results: Sludge and Fly Ash within 100 Miles (Continued)

Port	Site	Tech	Volume (10^6tons)	Dist. (n.m)	Max Trip (#)	Vessel (#)	Total Cost (10^6\$)	Unit Cost (\$/ton)
4	4	1	1.8	287	120	1	32.68	18.32
4	4	2	1.8	287	112	1	42.82	24.00
4	4	3	1.8	287	104	1	51.19	28.69
4	4	4	1.8	287	101	1	37.89	21.24
4	5	1	1.8	782	50	2	61.20	34.31
4	5	2	1.8	782	49	2	79.72	44.69
4	5	3	1.8	782	47	2	91.77	51.44
4	5	4	1.8	782	46	2	77.14	43.24
5	4	1	0.4	851	50	1	25.99	66.65
5	4	2	0.4	851	49	1	34.77	89.16
5	4	3	0.4	851	47	1	39.49	101.27
5	4	4	0.4	851	47	1	35.50	91.02
5	5	1	0.4	920	44	1	26.20	67.17
5	5	2	0.4	920	42	1	34.98	89.68
5	5	3	0.4	920	41	1	39.70	101.79
5	5	4	0.4	920	41	1	35.70	91.54

Notes: See notes for Table 15.

ports with relatively small waste volumes. For example, in Table 15, the unit cost is $111.02 per ton for the transportation system between the port of Galveston and the Gulf site using the Direct Descent Disc. This suggests that the design vessel capacity is too large for this port, and that using a smaller vessel may lead to lower costs.

Of the four technologies examined, Surface Emplacement consistently provides the least cost solution, while, in most cases, the Disc is the most costly technology. As expected, the relative cost levels are influenced by distance, unloading time and other factors. For example, as shown in Table 18, the unit cost of the Pipe Riser is the highest for the system between New York and Atlantic 1. This is because the unloading time for the Pipe Riser is the longest among the four technologies (Table 10). Thus, the vessel can only make 60 trips annually. In this case, for the given waste volume (3 million tons), three vessels are needed. By contrast, using other technologies, two vessels will be sufficient to carry the wastes.

We conducted sensitivity analyses to further examine the marine cost results. To simplify our analysis, we consider only Surface Emplacement here. The relationship between waste volume in a port and costs is illustrated in Figure 21. The distance is fixed at 787 nautical miles (New York to Atlantic 1). As the waste volume rises from 0.1 to 6 million tons, the total cost increases from $23 to $140 million per year and the unit cost decreases from $229 to $24 per ton. Figure 22 is similar to Figure 21, showing number of vessels instead of total cost. Because of the fixed vessel capacity, each increase in system capacity is discrete. Figure 22 shows that as waste volume increases, the number of vessels rises from one to four, while the unit cost curve has corresponding discontinuities. The unit cost rises whenever an additional vessel is added to the fleet, and declines as the fleet is more fully utilized.

Figure 21. Unit and Total Cost
Port to Site (787 nautial miles,tech 1)

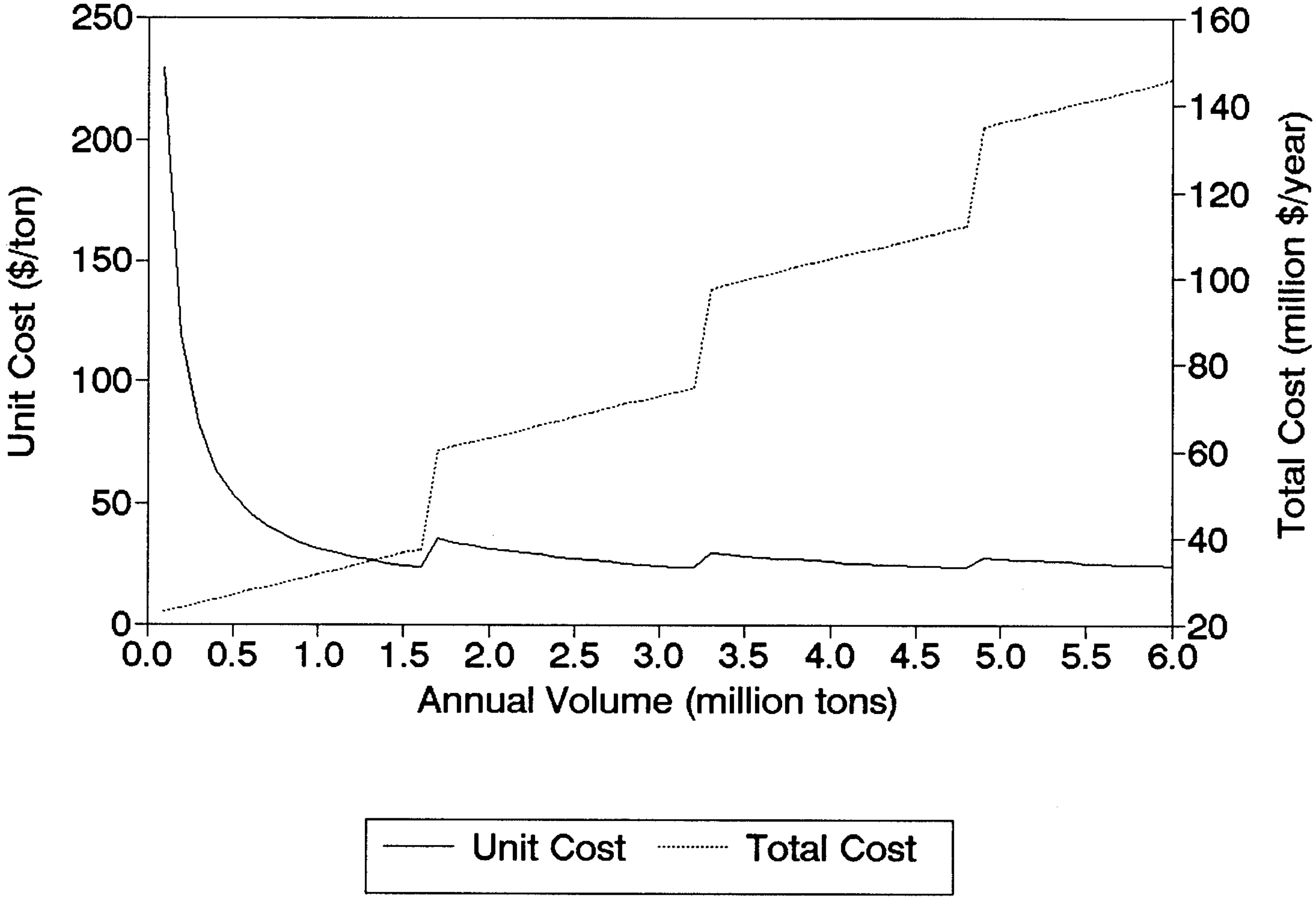
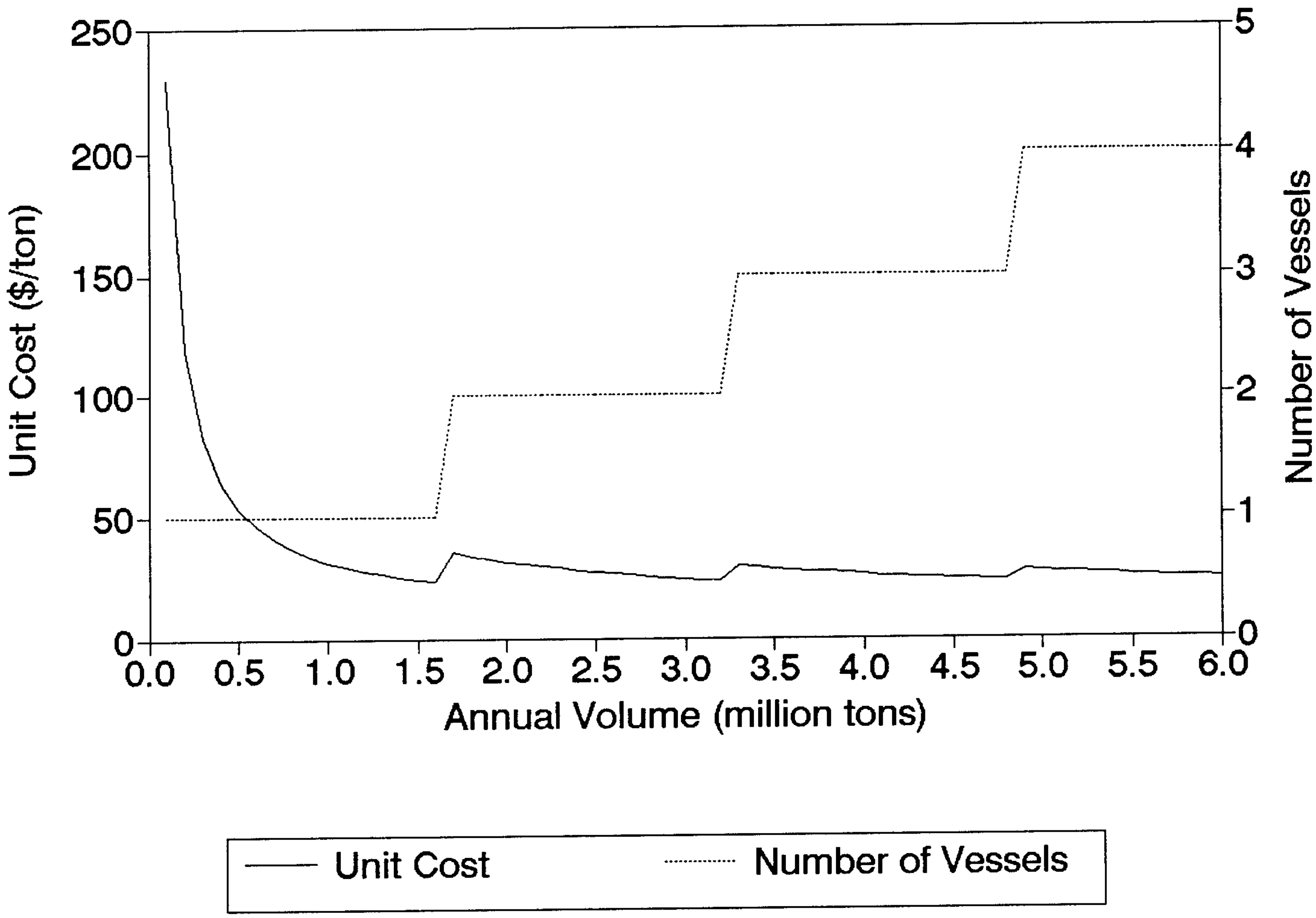


Fig.22. Unit Cost and Number of Vessels Port to Site (787 nautial miles,tech 1)



Results of sensitivity analyses on transit distance are shown in Figures 23 and 24. For a waste volume of 2.8 million tons (sludge and combined ash in New York), as one-way distance increases from 100 to 1,500 nautical miles, the total cost of the transportation system rises from \$35 to \$130 million per year, and the unit cost increases from \$12 to \$46 per ton, as shown in Figure 23. For the same variation in one-way distance, the transportation system requirement is depicted in Figure 24. The fleet size increases from one to four vessels, because the maximum number of round-trips per vessel per year decreases from 274 to 37.

The four technologies examined in this study are largely in the conceptual design stage. The above engineering cost assessment does not include costs associated with developing these new technologies. Development costs may include component testing, detailed design, and prototype building and testing. Also, as noted in the Introduction to this report, the results of some studies have indicated that cost estimates for projects using commercially unproven technologies are not only characteristically biased low, but are so uncertain that they cannot be relied upon at all (Merrow, Chapel, and Worthing, 1979; Merrow, Phillips, and Myers, 1981). To address these concerns, we performed sensitivity analyses with respect to capital cost estimates.

As shown in Equation (32), the capital costs in Table 12 are increased by a factor ranging from one to three. Again we consider the transportation system using Surface Emplacement technology between New York and Atlantic 1, and a waste volume of 2.8 million tons. As shown in Figure 25, as the capital cost adjustment factor rises from one to three, the unit cost increases from \$25.14 per ton (see Table 15) to \$47.71 per ton. When the capital cost is increased by 50 percent and 100 percent, the increase in unit cost is 22 percent (\$30.78 per ton)

Figure 23. Unit and Total Cost
Port to Site (2,841,000 tons, tech 1)

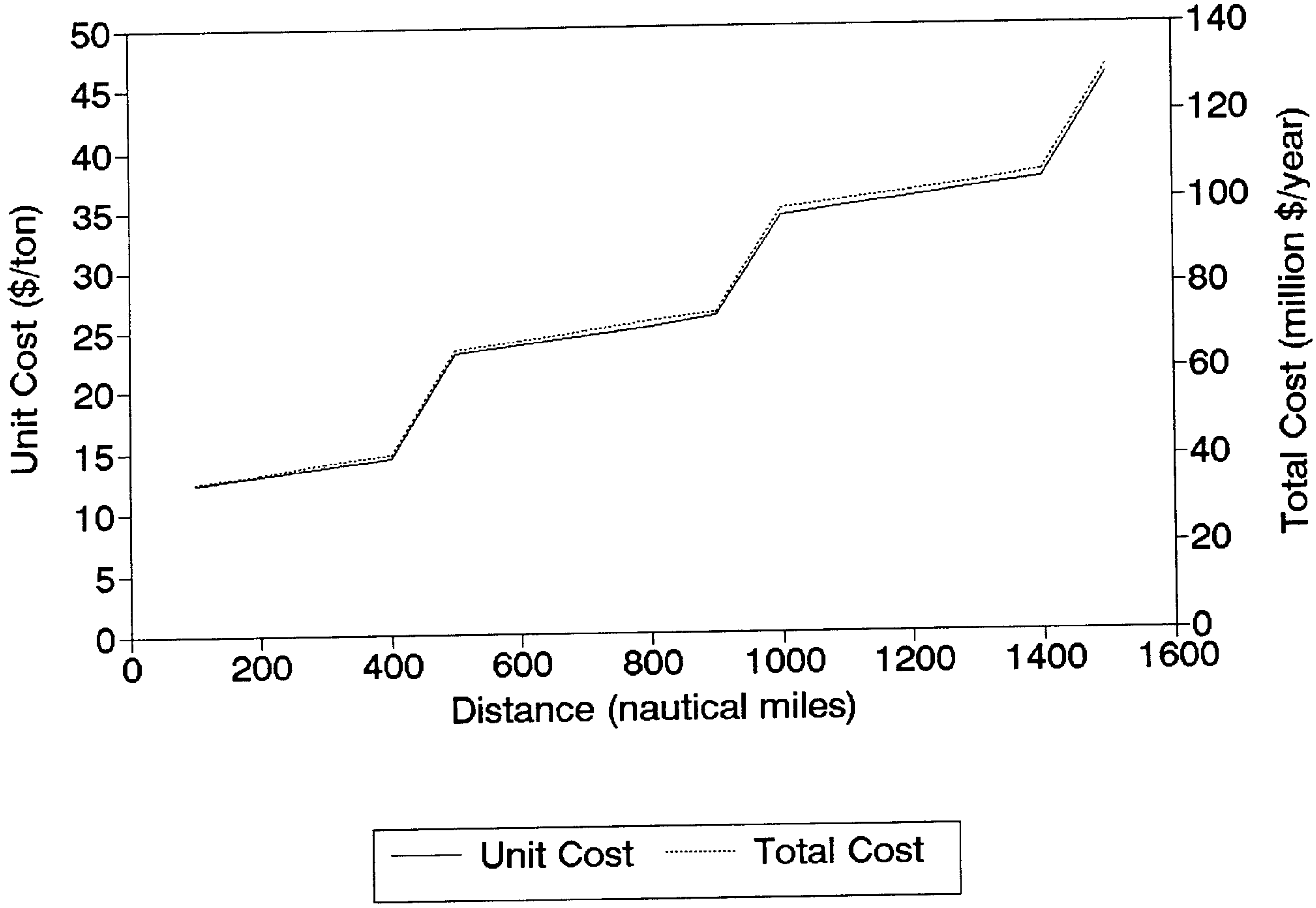


Figure 24. System Requirement
Port to Site (2,841,000 tons, tech 1)

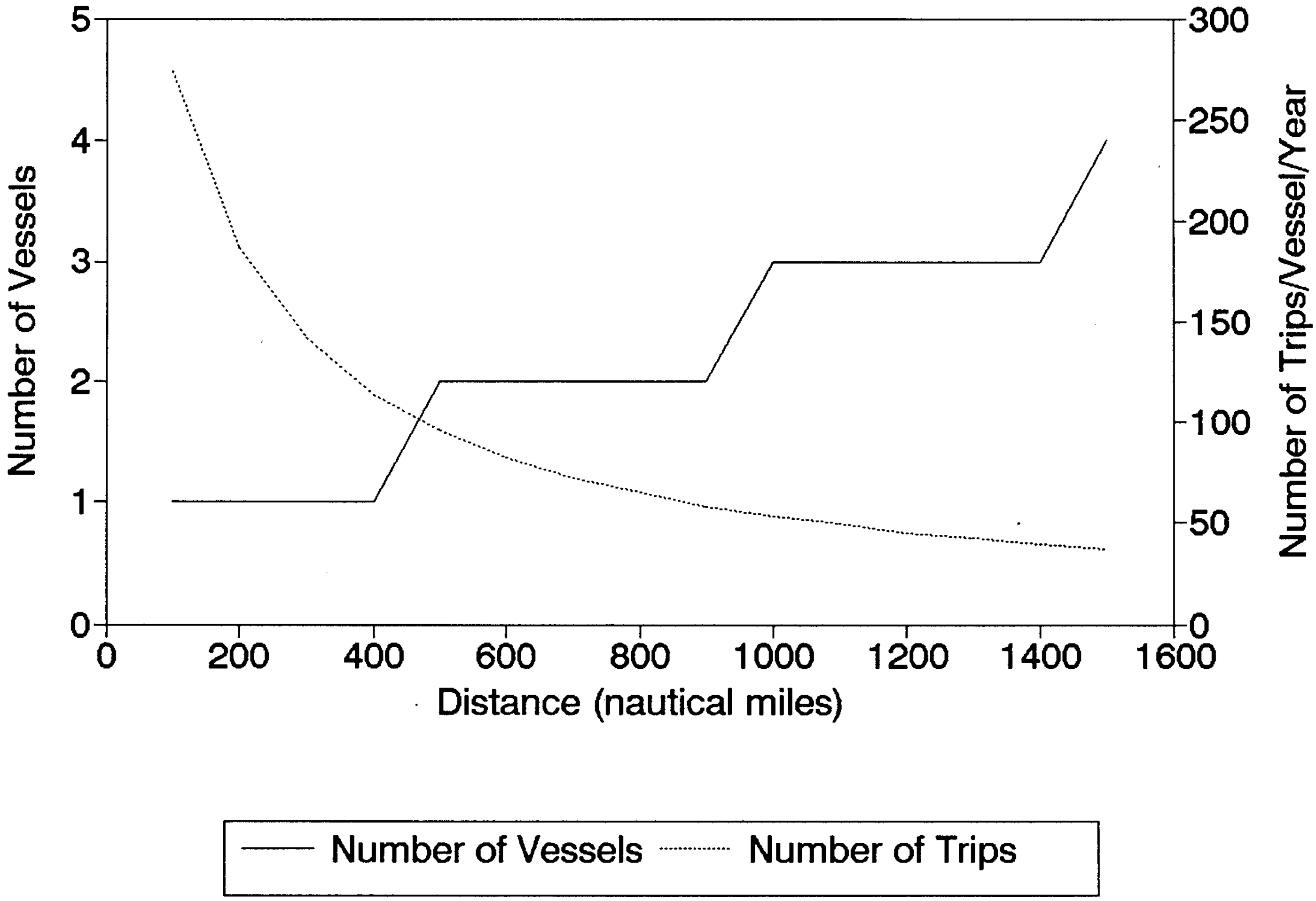
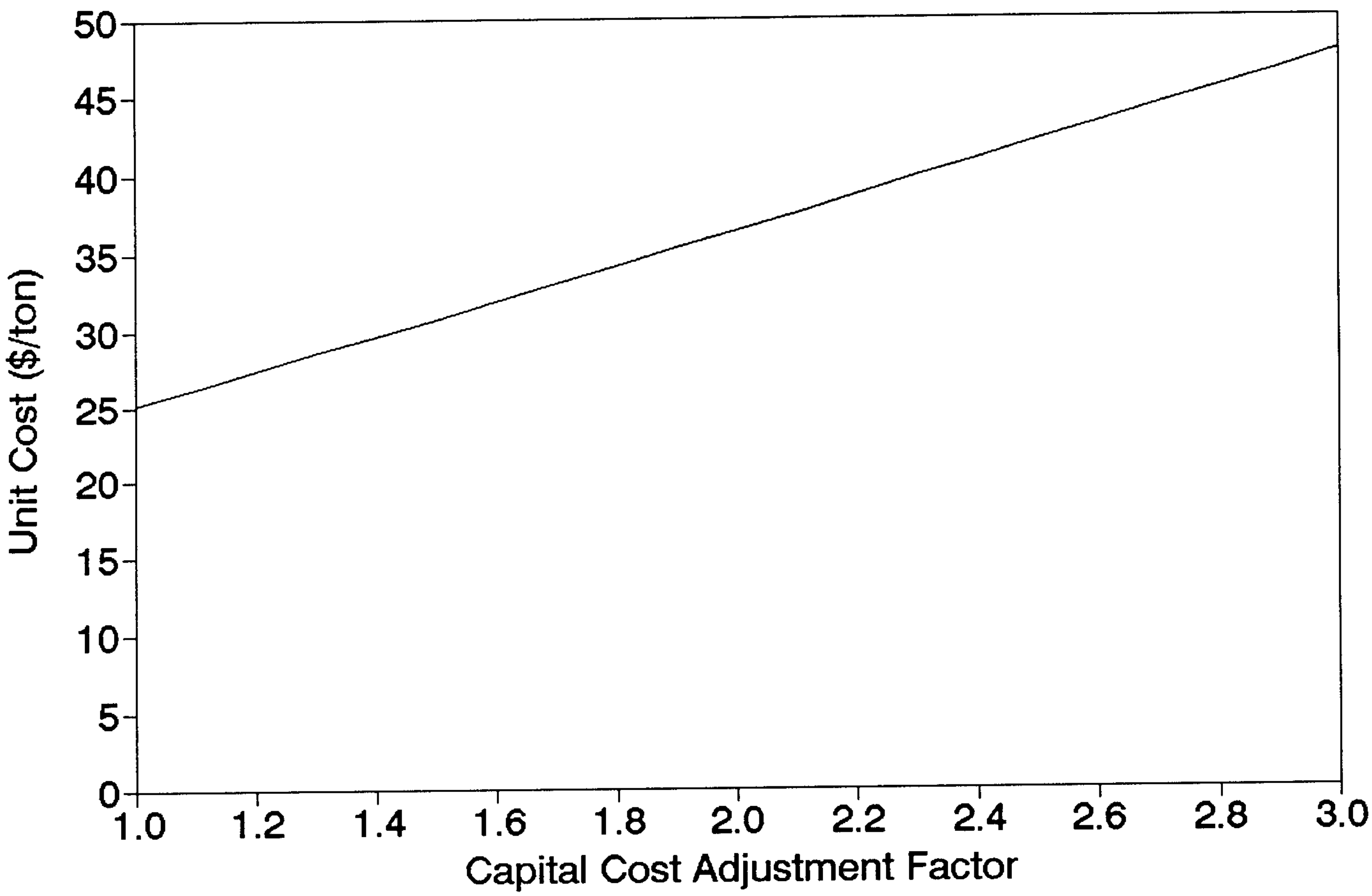


Figure 25. Unit Costs at Different Capital Cost Estimates



and 45 percent ($36.42 per ton), respectively.

3.3. Total Cost of the Ocean Option

The total cost of abyssal seafloor waste isolation consists of internal cost and external cost. The costs estimated in the preceding sections represent internal cost. In this case, internal cost includes transportation costs for both terrestrial and marine segments, and disposal cost at the abyssal sites. The cost of environmental monitoring equipment at ports is also included.

As shown in Figure 17, when the source-to-port distance is 80 miles, the unit cost is between $15.60 to $16.00 per ton for a wide range of waste volumes. Figure 19 indicates that when the waste volume is 118,000 metric tons (150,000 cubic yards of sludge at 20 percent solid), the unit cost is $10.47 per ton at 50 miles. It can be as low as $2.10 per ton at 5 miles and as high as $19.10 per ton at 100 miles. Also, the average regional source-to-port cost is affected by the waste volume profile of the region (see Figures 7 through 11 for sludge and Figures 12 through 15 for ash). The simulation results lead to a general conclusion: the average unit cost is below $10 per ton for waste within a 50 mile radius and below $20 per ton within a 100 mile radius.

The unit cost for the marine segment is also influenced by volume, distance and other factors. For New York to Atlantic 1, when the regional waste volume is relatively small (such as sludge and fly ash within 50 miles), the unit cost ranges from $33.65 to $50.41 per ton depending on the type of technologies utilized (see Table 16). For a larger waste volume (sludge and combined ash within 100 miles), the unit cost ranges between $23.35 and $41.52 per ton (see Table 17).

If we employ the least costly technology, Surface Emplacement, a conservative estimate of the combined cost of the land and marine segments would be $43 per ton for both the 50 mile and the 100 mile radius at New York. It is interesting to note that for a fixed vessel capacity (25,000 dwt), there is a tradeoff between land and marine unit costs. As land transportation distance increases, land unit cost also increases. However, as the radius increases, the regional waste volume becomes larger, and as a result, the unit cost for the marine segment decreases. Because of scale economies in shipping, this would still be true, though perhaps less pronounced, if the fixed capacity constraint were relaxed.

The WHOI (1993) study speculated that the cost associated with the abyssal ocean option might be significantly higher than that of offshore sludge dumping as practiced historically from New York, for instance. However, the unit cost estimates for the marine segment in this study are not much higher than those estimated in the NRC (1984) study. The NRC study provided unit cost estimates for several proposed sludge transportation systems at a one-way distance of 200 kilometers (108 nautical miles). Their estimated unit cost was between $10 and $20 per ton (at 20 percent solid), depending on vessel type and sludge throughput. In the NRC study, the sludge was transported at 3 percent solid, and the largest barge size was 7,500 dwt. The vessel capacity in our study is 25,000 dwt and sludge is transported at 20 percent solid. The cost escalation associated with increased distance is partially offset by economy of scale in the marine system.

The external cost of abyssal ocean waste isolation should include damages to marine resources, the environment in general, and to human health. This cost may be divided into two components. The first is external cost associated with accidental discharge of wastes into the

marine environment as a result of operational error or other accidents. We believe this would be small, since the expected waste volume spilled would be small. This component requires further examination.

The second component is the external cost associated with damage at the abyssal ocean sites. An earlier study (Jin 1994) has shown that the expected external cost of offshore sludge dumping is much smaller (below one dollar per ton) than corresponding internal costs. However, the variance of external cost is large because the damage to the marine environment and ecosystem is highly uncertain. Some study results (Squires 1983; Swanson *et al.* 1991) indicate that the external cost associated with ocean dumping at New York's 12-Mile Site could be much higher than its internal cost.

Although there is uncertainty associated with the external costs of abyssal site disposal, the cost may be much smaller than that of nearshore sites. This is because

> The vast deep abyssal hills and plains of the mid latitude regions of the Atlantic and Pacific Oceans are deserts. Life is sparse and mineral wealth almost non-exist.... We [marine scientists] now have the knowledge to assess which ocean environments *may* be suitable, or not suitable, repositories or disposal sites for many wastes.
>
> Optimal waste management programs must be designed to minimize risks to human health and the environment.... Our current understanding of the probability of impact to man from the use of abyssal ocean sites leads many of us [marine scientists] to believe that they may, in many instances, provide reduced risk and more optimal opportunities for future waste management schemes (Spencer 1991).

Based on these arguments, we speculate that the expected external cost of the abyssal ocean option *may* be relatively small. Additional economic research on this topic is needed, as outlined in the WHOI (1993) study. Clearly, future improvements in external cost assessment

will also depend on advancements in the marine sciences.

4. OPTIMAL WASTE MANAGEMENT AND THE OCEAN OPTION

As noted, estimates of the cost of abyssal seafloor waste isolation should consider the full range of costs likely to be incurred, including both direct (internal) costs and environmental (external) costs, and encompassing all costs from "upstream" management options such as conservation, waste reduction, and recycling to "downstream" costs such as transportation and systems operation. The economic feasibility of the abyssal ocean option depends on its cost relative to land-based waste management options. The cost of these land-based technologies should also be estimated addressing the full range of costs mentioned above.

4.1. Optimal Waste Management

A region's waste management problem should be analyzed in an optimization framework that incorporates the ocean option along with waste reduction and land-based disposal alternatives (Jin *et al.* 1993). The objective of optimization is to maximize net social benefit, defined as the social benefit from production and consumption minus associated costs, including those of waste management. An optimal waste management strategy considers the trade-off between upstream pollution control options (recycling and source reduction) and down-stream disposal options, the trade-offs among various disposal options (including the ocean option), and the trade-off between economic development and quality of the environment.

In a simplified scenario, the waste disposal problem for a region is to minimize total disposal cost. However, decisions concerning the appropriate mix of waste disposal options are extremely complicated in practice due to the inherent difficulties in quantifying the environmental consequences of available disposal options, and due to uncertainties associated with some of the

costs of disposal. Further complications arise from the fact that the environmental consequences of waste disposal are location- and waste-specific, and the public is strongly opposed to virtually all forms of waste disposal located nearby (Jin 1994). The development of internal cost estimates for waste management options is the first, and critically important, step in this process.

The current situation on sludge generation and management practices in New York City is described in Table 19 (NYC DEP 1994; also see Swanson 1993). The City has 14 water pollution control plants, and their sludge is dewatered to 28 percent solid in eight facilities. Total output from the eight dewatering facilities is 312 dry tons (100% solid) per day. As indicated in Table 19, there are four contractors involved in sludge management. NYOFCO, Merco and Chambers routinely receive dewatered sludge, while Star is a back-up contractor. As explained in the Notes of Table 19, the current management practice emphasizes beneficial uses.

The cost of sludge management is the payment made by the City to these contractors. The payment is composed of two parts: (i) a lump sum monthly payment independent of the actual sludge quantity handled by the contractor, and (ii) an additional payment calculated as the product of the actual sludge quantity handled and the unit price listed in the third column of Table 19. The total unit cost per dry ton and the cost per ton at 20 percent solid are shown in the last two columns of Table 19, respectively. These costs include both transportation and disposal. Most of the sludge is managed at a unit cost above $160 per ton (20 percent solid).

Multimedia disposal of sewage sludge in New Jersey between 1983 and 1992 (NJ DEPE 1993) is summarized in Table 20. Prior to the implementation of the Ocean Dumping Ban Act of 1988, more than one half of the sludge was disposed of in the ocean at the 12-Mile and 106-

Table 19. New York City Sludge Management Costs

Contractor	Dry Tons/Day	Unit Price $/ton (28% solid)	Lump Sum $/month	Total Unit Cost $/dry ton	Total Unit Cost $/ton (20% solid)
NYOFCO	220	59	4,145,000	839	168
Merco	71	96	980,000	803	161
Chambers	21	65	115,500	415	83
Star	0	68	0	243	49
Total	312	-	5,240,500	-	-

Notes:

NYOFCO: NYOFCO has constructed, owns and operates a pelletization facility. All dewatered sludge is thermally dried into pellets which are beneficially used as follows:

- Colorado - land application onto wheat fields;
- Ohio - mixed with top soil and used as final vegetative landfill cover; and
- Florida - the pellets are sold to fertilizer blenders at approximately $40-$70 per ton (28% solid) for use on citrus groves. The NYC DEP receives approximately 45% of the gross from these sales.

Merco: The dewatered sludge is beneficially used as follows:

- Texas - applied onto desert rangeland, which has been stripped of its native grasses due to a combination of drought and overgrazing, to restore grasses for grazing and wildlife to the area; and
- Arizona - land application onto hay, grain and cotton crops.

Chambers: The dewatered sludge is disposed of at a landfill in Virginia.

Star Recycling: Star is a back-up landfill contractor that remains on standby. When Star is allocated dewatered sludge, it is disposed of at a landfill in Ohio.

Table 20. 1983-1992 New Jersey Sludge Management: Percentage of Sludge Managed by Technologies

Technologies	1983	1986	1989	1992
Ocean Disposal	55.5	52.6	50.8	0.0
Incineration	4.4	16.8	19.0	20.5
Landfill	30.7	0.0	0.0	0.0
Land Application	6.0	11.0	11.2	22.2
Out of State	0.1	15.3	16.9	56.6
Other	3.3	4.3	2.1	0.7
Total	100.0	100.0	100.0	100.0

mile Sites. The quantities managed through incineration and land application have been increasing. There has been no landfilling of sludge in New Jersey since 1986. The termination of ocean dumping lead to a drastic increase in sludge shipments to other states. In 1992, nearly 57 percent of New Jersey sludge was transported to out-of-state facilities. The range of sludge management costs in various New Jersey facilities (NJ DEPE 1993) is shown in Table 21. Low-end costs are about $30 per ton (20 percent solid) and high-end costs are above $100 per ton. The highest cost is the same as that of New York City ($168 per ton).

Ash disposal costs in the United States (Berenyi and Gould 1993) are listed by region in Table 22. The costs include both transportation and disposal. In the Northeast, the cost ranges from $15.50 to $104.00 per ton with a mean of $48.15 per ton.

As noted, the unit cost of abyssal seafloor waste isolation is about $43 per ton for the New York area. This cost can be higher if external cost is higher or the engineering system is more costly than expected (see Figure 25), but it can also be lower if the engineering system is optimized with respect to vessel capacity, system options, and waste volumes for a specific port. Thus, the abyssal ocean option may be economically competitive even at the present time. However, the abyssal ocean option may not be competitive in other areas due to their limited waste volumes.

4.2. Policy Constraints on the Ocean Option

The elements of an optimal waste management policy must be technologically and economically feasible. In addition, they must be politically acceptable, since the interpretation of uncertainties about environmental and human health costs often takes place in the political

Table 21. Sludge Management Costs in New Jersey

Technologies	Unit Cost $/dry ton	Unit Cost $/ton (20% solid)
Incineration	109-480	22-96
Composting	175-840	35-168
Land Application	152-650	30-130

Table 22. Ash Disposal Costs in the United States by Region

Region	Mean ($/ton)	Minimum ($/ton)	Maximum ($/ton)
Northeast	48.15	15.50	104.00
South	26.07	2.50	110.00
Northcentral	36.19	5.00	68.00
West	27.13	5.00	50.00

arena, and popular or political opposition can preclude an option from being implemented. Here, the ocean option encounters perhaps its most significant obstacles.

How realistic is it to consider the ocean option for waste disposal in the United States today? At present, it is illegal in the United States to dump, or transport for the purpose of dumping, sewage sludge or industrial waste into ocean waters (not just the territorial waters or exclusive economic zone of the United States) under the Ocean Dumping Ban Act. Under international conventions, dumping of industrial waste in international waters is to be eliminated by 1996 (IMO, 1990); dumping of sewage sludge requires a general permit under the London Dumping Convention.

Moore (1992) provides a brief review of ocean waste disposal practices. Between 400 million and 1.2 billion tons of waste materials were disposed of in the oceans worldwide each year during the 1980s. Dredge spoils and sewage sludge made up most of it: some 400 million tons and eight million wet tons, respectively, in the United States alone during the 1980s. Since the Ocean Dumping Ban Act (see below), dredged material is now virtually the only waste directly disposed of in the ocean from the United States. However, direct disposal (dumping from ships and barges) only accounts for perhaps one tenth of the anthropogenic waste entering the oceans. Sewage and storm runoff via drains and outfalls, agricultural runoff, and other non-point sources contribute the major part of ocean waste disposal.

Early attempts to curb ocean dumping in the United States included the Rivers and Harbors Appropriation Act of 1899 (Refuse Act, Ch. 425, 20 Stat. 1121), which prohibited ships and shore facilities from dumping "any refuse matter of any kind or description whatever other than that flowing from streets and sewers and passing therefrom in a liquid state, into any

navigable water of the United States" (33 USC 407). The Refuse Act was narrowly interpreted and only reluctantly enforced by the designated agency, the U.S. Army Corps of Engineers (Moore, 1992).

The Refuse Act was largely supplanted by the Federal Water Pollution Control Act (FWPCA) of 1948 (33 USC 1251ff), as amended by the Clean Water Act (CWA) of 1972 (33 USC 1251-1387), and by the Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1972 (33 USC 1401ff). Among other things, CWA regulates discharges from pipelines and vessels in estuaries and certain coastal waters, and from sources other than vessels beyond the territorial sea. MPRSA governs the dumping of waste in and beyond the territorial sea. FWPCA, MPRSA and their subsequent amendments gradually ended the traditional practice of unrestricted ocean dumping in U.S. waters through restrictions and permit requirements. MPRSA has been amended repeatedly, including a change to bring it into conformance with the provisions of the London Dumping Convention.

The London Dumping Convention. "A Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter" (London Dumping Convention, LDC, 11 *International Legal Materials* 1291) was adopted by an intergovernmental conference in London in 1972 and entered into force in 1975. As of 1990, it had 64 Contracting Parties, including the United States, which initiated the discussions that led to the Convention. The International Maritime Organization (IMO) was designated as responsible for secretarial duties.

The Convention requires Contracting Parties to establish national systems to control dumping at sea of wastes and other matter. "The main aim of the Convention is to prevent indiscriminate disposal at sea of waste chemicals and minerals, on the understanding that the

sea's capacity to assimilate waste and to regenerate natural resources is not unlimited. The dumping of certain categories of waste will be prohibited or subject to permit." The Convention covers all marine waters other than the "internal waters"[2] of Contracting Parties. It defines "dumping" broadly as "any deliberate disposal at sea of wastes or other matter" (III.1.(a)(i)), but excluding "placement of matter for a purpose other than the mere disposal thereof, provided that such placement is not contrary to the aims of this Convention" (III.1.(b)(ii)). This suggests that placement of waste on the seafloor for research purposes might not be governed by the Convention.

A "black list" of the following substances may not be dumped at all under LDC, except in trace concentrations or when otherwise rendered harmless by the marine environment: mercury, cadmium, and their compounds; organohalogen compounds (e.g. DDT and PCBs); persistent plastics; and crude oil and petroleum byproducts. Dumping of high-level radioactive wastes and chemical and biological warfare agents is prohibited under all circumstances. A "grey list" of wastes requires special permits, and includes arsenic, lead, copper, zinc, and their compounds; cyanides; fluorides; organosilicon compounds; pesticides not in the black list; low-level radioactive waste; and items (such as containers) that could present obstacles to navigation or fishing. Dumping of all other substances requires a general permit. All permits are to be issued by the cognizant national authorities (e.g. the Environmental Protection Agency in the United States).

Consultative meetings of the Contracting Parties are held at intervals of one or two years

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[2] LDC does not define "internal waters." As used in the Law of the Sea Convention, "internal waters" are "waters on the landward side of the baseline of the territorial sea" (Article 8, UN, 1982).

to develop ocean dumping policies beyond the Convention itself. At the 13th consultative meeting, held in 1990, the Parties agreed to end ocean disposal of industrial wastes by the end of 1995 (IMO, 1990).

The Law of the Sea Convention. The United Nations Convention on the Law of the Sea (UN, 1982) contains provisions governing ocean dumping (Articles 210 and 216), as well as other forms of marine pollution. The United States became a signatory to the Law of the Sea Convention (LOS) in 1994.

Article 210 requires states to adopt laws for the control of ocean dumping that are no less effective than existing global standards (e.g., the London Dumping Convention). Coastal states are given the right to permit and control ocean dumping in their territorial seas, exclusive economic zones, and continental shelf areas. Article 216 deals with enforcement of ocean dumping rules, and gives powers of enforcement to coastal states (for dump sites), flag states (via registry of vessels engaged in dumping), and port states (where waste loading may occur). The effect of LOS on ocean dumping is to elevate the provisions of the London Dumping Convention to a minimum standard for the regulation of ocean dumping by all LOS signatories.

MPRSA and the Ocean Dumping Ban Act. In the United States, implementing legislation for the London Dumping Convention is contained in the 1974 and 1980 amendments to the Marine Protection, Research, and Sanctuaries Act (MPRSA), also known as the Ocean Dumping Act. Under MPRSA, the Environmental Protection Agency (EPA) has responsibility for permits governing all ocean disposal of all materials except dredge spoils, which are administered by the Army Corps of Engineers. (Even for dredge spoils, EPA has oversight responsibility, and must designate disposal sites.) EPA can issue five types of permits for ocean disposal: general (burial

at sea, target vessels for Navy exercises, and certain scrap vessels); special (the Ocean Dumping Regulations, 40 CFR 227, require consideration of environmental effects, need, alternatives, and effects on aesthetic, recreational, and economic uses of the ocean; for a maximum of three years); emergency (imminent risk to human health and no feasible alternative; last issued in 1984); interim (maximum one year, rarely used); and research.

In November 1988, Congress amended MPRSA by passing the Ocean Dumping Ban Act (ODBA) of 1988 (P.L. 100-688, various sections of 33 USC) to phase out the dumping of municipal sewage sludge and industrial waste by the end of 1991. "After 12/31/91, it shall be unlawful for any person to dump into ocean waters, or to transport for the purposes of dumping into ocean waters, sewage sludge or industrial waste" (Section 104B(a)(1)(ii) of MPRSA as amended by ODBA). "Ocean waters" are not specifically defined in the law, and the term appears to apply broadly. The last major dumping operation, for sewage sludge from the New York City area, ceased in June 1992.

MPRSA and ODBA exempt from their definition of "dumping" those discharges from outfalls subject to provisions of other legislation, including the Clean Water Act (CWA). Although the 1981 amendments to CWA prohibit the discharge of sewage sludge into the ocean via outfalls, exemptions can be and have been obtained (e.g., Boston). As a result, some sewage continues to be disposed of in U.S. nearshore waters. Transport of sewage sludge and industrial waste for deep-sea disposal, however, is illegal and has ceased. ODBA (section 1003) also repealed the MPRSA provision for "research permits" for dumping as part of research projects.

From a legal standpoint, therefore, the revival of the ocean disposal option for sewage sludge would require modification of the Ocean Dumping Ban Act, and an EPA permit and site

designation for dumping (an LDC "general permit"). Industrial waste may face more serious legal obstacles, since LDC consultative meetings appear to be leading to an international ban on dumping such wastes (as presently formulated, this ban would not encompass sewage).

Public perceptions and fears had much to do with the elimination of the ocean option for waste disposal. Ironically, the events that fueled public pressure for the ban on ocean dumping, including algal blooms (e.g., off Long Island, summer 1987), hospital waste washups (New Jersey, summer 1987, 1988), dead fish washups (New York, New Jersey, summer 1988), and sewage washups (Quincy, Massachusetts, 1980s) -- and associated beach closures -- likely were not caused by the activity that was banned as a result, the offshore disposal of sewage sludge. Nonetheless, public perception and politics will play a major role in any debate over a reconsideration of the ocean option, and represent prominent topics for additional policy research.

5. CONCLUSIONS

In this study, we have developed an integrated analytical framework that captures major economic, engineering, geographic and social factors affecting the cost of abyssal seafloor waste isolation, and can be used to generate quantitative estimates of the *internal* cost of this option. Using this analytical framework, we have developed systematic cost estimates for engineering systems transporting wastes from sources to a port and from that port to an abyssal ocean disposal site. Specifically, we examined two waste streams, sewage sludge and ash from municipal incinerators, in five metropolitan areas: New York, Miami, Galveston, Los Angeles and Seattle, and five related abyssal disposal sites. We have discussed the cost of the abyssal ocean option in the context of a multimedia waste management framework, and assessed the cost competitiveness of the ocean option. Our study leads to the following conclusions:

- The New York area has the largest waste volume of the five areas examined. Sludge (at 20 percent solid) and combined ash (wet) volume in the area increases from 2.8 million tons within 50 miles to 4.8 million tons within 100 miles of the port. The total waste volumes in the other four regions are significantly smaller and concentrated within a 50 mile radius. At a 100 mile radius, Los Angeles has less than 2 million tons of sludge and combined ash, Miami has 1.2 million tons, and Galveston and Seattle each has less then 0.5 million tons.

- The unit cost of source-to-port transportation using large trucks is below $10 per ton for waste within a 50 mile radius and below $20 per ton within a 100 mile radius. The cost varies with waste volumes, and the average unit cost for a region depends on the distribution of waste as a function of distance from port.

- The unit cost of port-to-site transportation and disposal is also affected by waste

volume, distance and other factors. For the four marine system concepts developed by Oceaneering Technologies, and assuming transport from New York to Atlantic 1, the marine segment unit cost ranges from \$33.65 to \$50.41 per ton when the regional waste volume is relatively small (sludge and fly ash within 50 miles). For a large waste volume (sludge and combined ash within 100 miles), the unit cost ranges between \$23.35 and \$41.52 per ton.

• It has been speculated that the cost associated with the abyssal ocean option might be significantly higher than that of offshore sludge dumping as practiced historically. However, the unit cost estimates for the marine segment in this study are not much higher than those estimated in the NRC (1984) study. This is because vessel capacity in our study is much larger, and the cost escalation due to increased distance is partially offset by economies of scale of the marine transport system.

• The cost of the abyssal ocean option may exceed our estimates if external cost is higher or the engineering system more costly than we have assumed, but it may also be lower if the engineering system is optimized with respect to vessel capacity, system options, and waste volumes for a specific port.

• For the least costly marine transport technology, Surface Emplacement, a conservative estimate of the combined cost of the land and marine segments would be \$43 per ton for both the 50 mile and the 100 mile radius at New York. Interestingly, for a fixed vessel capacity (e.g., 25,000 dwt), there is a tradeoff between land and marine unit costs. As land transportation distance increases, unit cost also increases. However, as the radius increases, regional waste volume becomes larger, and as a result, the unit cost for the marine segment decreases.

• In New York City, most of the sludge is currently managed at a unit cost above $160 per ton (20 percent solid). The mean ash disposal cost is $48 per ton in the Northeast and higher in the New York area. Since the unit cost of abyssal seafloor waste isolation is about $43 per ton for the New York area, the abyssal ocean option may be economically competitive even at the present time in this region. However, the abyssal ocean option may not be competitive in other areas due to their limited waste volumes.

As noted, this study focuses on an assessment of the internal cost of abyssal seafloor waste isolation – the first, and critically important, step in the analysis of the economics of the abyssal ocean option. There are a number of extensions to be addressed in future studies:

• Contaminated dredged material is not covered in this study due to lack of data at the present time. However, more data will become available as EPA develops its National Inventory of Sites with Sediment Contamination (EPA 1994b). With the new data, the analytical framework developed in this study can easily be applied to dredged materials.

• The internal cost assessment can be significantly refined for a specific port, such as New York. The integrated model developed in this study can be extended to include plant-based sludge quantity estimation, and to optimize vessel capacity and system configuration.

• The estimation of external cost can be developed by constructing an environmental damage function based on expert judgement, and by assessing opposition cost and public risk perception, as described in the WHOI (1993) report. Also, the probability of accidental discharge of wastes into the marine environment will be quantified.

• The study can be extended to consider the dynamics of waste management. Such an extension would consider both current and future demand for ocean disposal, and the conditions

under which this demand is likely to grow. Since the environmental effect of ocean disposal is highly uncertain, the environmental costs associated with the ocean option are uncertain. Scientific research can lead to a reduction in that uncertainty. Further work could examine the effect of scientific research and learning on waste management strategies. An improved integrated model would be useful not only for the evaluation of the ocean option in different regions, but also for overall waste management decisions in those regions.

• Finally, this study can be extended to examine the policy and legal issues associated with the abyssal ocean option. In particular, it is of interest to consider in more detail the legal and political changes necessary to enable consideration of the ocean option in practice, assuming that it is economically justifiable.

APPENDIX 1

Table A1. Population Distribution by Distance from Port of New York

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
NY	RICHMOND	378977	SAINT GEORGE	6
NJ	ESSEX	778964	NEWARK	6
NJ	HUDSON	553099	JERSEY CITY	6
NJ	UNION	493819	ELIZABETH	12
NY	NEW YORK	1487536	NEW YORK	14
NY	KINGS	2300664	BROOKLYN	15
NJ	BERGEN	825380	HACKENSACK	21
NY	BRONX	1203789	BRONX	22
NJ	PASSAIC	453060	PATERSON	26
NJ	MIDDLESEX	671811	NEW BRUNSWICK	27
NY	QUEENS	1951598	JAMAICA	30
NJ	MORRIS	421361	MORRISTOWN	35
NJ	SOMERSET	240245	SOMERVILLE	37
NY	WESTCHESTER	874866	WHITE PLAINS	38
NJ	MONMOUTH	553093	FREEHOLD	40
NY	NASSAU	1287444	MINEOLA	44
NY	ROCKLAND	265475	NEW CITY	47
NJ	HUNTERDON	107802	FLEMINGTON	50
NJ	MERCER	325824	TRENTON	54
NJ	SUSSEX	130943	NEWTON	57
NY	PUTNAM	83941	CARMEL	58
NJ	OCEAN	433203	TOMS RIVER	63
NJ	WARREN	91607	BELVIDERE	68
NY	ORANGE	307647	GOSHEN	68
NJ	BURLINGTON	395066	MOUNT HOLLY	69

Table A1. Population Distribution by Distance from Port of New York (Continued)

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
CT	FAIRFIELD	827645	BRIDGEPORT	69
PA	NORTHAMPTON	247105	EASTON	70
PA	PIKE	27966	MILFORD	72
PA	BUCKS	541174	DOYLESTOWN	74
PA	MONROE	95582	STROUDSBURG	77
NY	DUTCHESS	259462	POUGHKEEPSIE	84
PA	PHILADELPHIA	1585577	PHILADELPHIA	86
CT	NEW HAVEN	804219	NEW HAVEN	87
PA	LEHIGH	291130	ALLENTOWN	88
NJ	CAMDEN	502824	CAMDEN	88
NJ	GLOUCESTER	230082	WOODBURY	92
PA	MONTGOMERY	678111	NORRISTOWN	93
NY	SUFFOLK	1321768	RIVERHEAD	95
NY	SULLIVAN	69277	MONTICELLO	97
NY	ULSTER	165304	KINGSTON	101
PA	DELAWARE	547651	MEDIA	102
PA	CARBON	56973	JIM THORPE	111
NJ	ATLANTIC	224327	MAYS LANDING	113
CT	MIDDLESEX	143196	MIDDLETOWN	113
DE	NEW CASTLE	441946	WILMINGTON	114
PA	CHESTER	376396	WEST CHESTER	115
CT	LITCHFIELD	174092	LITCHFIELD	118
PA	WAYNE	39944	HONESDALE	121
PA	BERKS	336523	READING	121
NJ	SALEM	65294	SALEM	122
NJ	CUMBERLAND	138053	BRIDGETON	122

Table A1. Population Distribution by Distance from Port of New York (Continued)

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
PA	LACKAWANNA	219097	SCRANTON	124
NY	GREENE	44739	CATSKILL	125
NY	COLUMBIA	62982	HUDSON	126
CT	HARTFORD	852783	HARTFORD	127
PA	LUZERNE	328149	WILKES-BARRE	132
PA	SCHUYLKILL	152585	POTTSVILLE	133
MD	CECIL	71347	ELKTON	134
NJ	CAPE MAY	95089	CAPE MAY CT HSE	137
CT	TOLLAND	128699	ROCKVILLE	142
CT	NEW LODON	254957	NORWICH	143
PA	LANCASTER	422822	LANCASTER	145
PA	WYOMING	28076	TUNKHANNOCK	147
PA	LEBANON	113744	LEBANON	148
MA	HAMPDEN	456310	SPRINGFIELD	150
MA	BERKSHIRE	139352	PITTSFIELD	150
NY	ALBANY	292793	ALBANY	151
PA	COLUMBIA	63202	BLOOMSBURG	154
NY	RENSSELAER	154429	TROY	159
PA	MONTOUR	17735	DANVILLE	161
NY	SCHENECTADY	149285	SCHENECTADY	165
PA	DAUPHIN	237813	HARRISBURG	165
MD	HARFORD	182132	BAL AIR	165
MD	KENT	17842	CHESTERTOWN	166
NY	DELAWARE	47225	DELHI	167
MA	HAMPSHIRE	146568	NORTHAMPTON	167
DE	KENT	110993	DOVER	168

Table A1. Population Distribution by Distance from Port of New York (Continued)

STATE	COUNTY	POPU.	COUNTY SEAT	DISTANCE
NY	SCHOHARIE	31859	SCHOHARIE	168
PA	YORK	339574	YORK	168
PA	SUSQUEHANNA	40380	MONTROSE	169
CT	WINDHAM	102525	PUTNAM	170
RI	WASHINGSTON	110006	WEST KINGSTON	170
NY	BROOME	212160	BINGHAMTON	172
PA	NORTHUMBERLAND	96771	SUNBURY	173
RI	KENT	161135	EAST GREENWICH	175
MD	BALTIMORE	692134	TOWSON	177
MD	QUEEN ANNES	33953	CENTREVILLE	177
PA	UNION	36176	LEWISBURG	178
MD	BALTIMORE CITY	736014	BALTIMORE	179
PA	BRADFORD	60967	TOWANDA	185
MA	FRANKLIN	70092	GREENFIELD	186
RI	PROVIDENCE	596270	PROVIDENCE	187
RI	NEWPORT	87194	NEWPORT	188
MA	WORCESTER	709705	WORCESTER	188
PA	SULLIVAN	6104	LAPORTE	190
PA	SNYDER	36680	MIDDLEBURG	191
PA	LYCOMING	118710	WILLIAMSPORT	193
NY	CHENANGO	51768	NORWICH	198
RI	BRISTOL	48859	BRISTOL	199
DE	SUSSEX	113229	GEORGETOWN	203
MD	CAROLINE	27035	DENTON	203
NY	OTSEGO	60517	COOPERSTOWN	207

Table A2. Population Distribution by Distance from Port of Miami

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
FL	DADE	1937194	MIAMI	1
FL	BROWARD	1255518	FORT LAUDERDALE	25
FL	PALM BEACH	863503	WEST PALM BEACH	66
FL	MARTIN	100900	STUART	103
FL	GLADES	7591	MOORE HAVEN	107
FL	COLLIER	152099	NAPLES	109
FL	SAINT LUCIE	150171	FORT PIERCE	121
FL	HENDRY	25773	LA BELLE	122
FL	OKEECHOBEE	29627	OKEECHOBEE	125
FL	INDIAN RIVER	90208	VERO BEACH	135
FL	LEE	335113	FORT MYERS	146
FL	MONROE	78024	KEY WEST	162
FL	HIGHLANDS	68432	SEBRING	162
FL	CHARLOTTE	110975	PUNTA GORDA	170
FL	DE SOTO	23865	ARCADIA	175
FL	HARDEE	19499	WAUCHULA	199
FL	POLK	405382	BARTOW	209
FL	BREVARD	398978	TITUSVILLE	209
FL	SARASOTA	277776	SARASOTA	215
FL	OSCEOLA	107728	KISSIMMEE	216
FL	MANATEE	211707	BRADENTON	226

Table A3. Population Distribution by Distance from Port of Galveston

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
TX	GALVESTON	217396	GALVESTON	1
TX	HARRIS	2818199	HOUSTON	47
TX	BRAZORIA	191707	ANGLETON	52
TX	CHAMBERS	20088	ANAHUAC	65
TX	FORT BEND	225421	RICHMOND	68
TX	JEFFERSON	239389	BEAUMONT	78
TX	MATAGORDA	36982	BAY CITY	86
TX	LIBERTY	52726	LIBERTY	87
TX	MONTGOMERY	182201	CONROE	91
TX	WALLER	23389	HEMPSTEAD	94
TX	WHARTON	39955	WHARTON	97
TX	HARDIN	41320	KOUNTZE	98
TX	ORANGE	80509	ORANGE	100
TX	AUSTIN	19832	BELLVILLE	110
TX	SAN JACINTO	16372	COLDSPRING	114
TX	WASHINGTON	26154	BRENHAM	116
TX	WALKER	50917	HUNTSVILLE	118
TX	POLK	30687	LIVINGSTON	119
TX	COLORADO	18383	COLUMBUS	122
TX	JACKSON	13039	EDNA	133
LA	CALCASIEU	168134	LAKE CHARLES	135
TX	GRIMES	18828	ANDERSON	136
TX	CALHOUN	19053	PORT LAVACA	138

Table A3. Population Distribution by Distance from Port of Galveston (Continued)

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
TX	MADISON	10931	MADISONVILLE	143
TX	JASPER	31102	JASPER	146
TX	BRAZOS	121862	BRYAN	148
TX	TYLER	16646	WOODVILLE	151
TX	BURLESON	13625	CALDWELL	156
TX	FAYETTE	20095	LA GRANGE	159
LA	BEAUREGARD	30083	DE RIDDER	159
TX	LAVACA	18690	HALLETTSVILLE	159
TX	TRINITY	11445	GROVETON	160
TX	VICTORIA	74361	VICTORIA	160
TX	NEWTON	13569	NEWTON	161
TX	LEON	12665	CENTERVILLE	166
TX	ANGELINA	69884	LUFKIN	166
TX	HOUSTON	21375	CROCKETT	166
TX	LEE	12854	GIDDINGS	166
LA	JEFFERSON DAVIS	30722	JENNINGS	170
LA	CAMERON	9260	CAMERON	171
TX	MILAM	22946	CAMERON	171
TX	BASTROP	38263	BASTROP	177
LA	ALLEN	21226	OBERLIN	179
TX	ROBERTSON	15511	FRANKLIN	180
TX	SABINE	9586	HEMPHILL	182
TX	GOLIAD	5980	GOLIAD	186

Table A3. Population Distribution by Distance from Port of Galveston (Continued)

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
TX	GONZALES	17205	GONZALES	187
TX	NACOGDOCHES	54753	NACOGDOCHES	187
TX	DE WITT	18840	CUERO	188
LA	ACADIA	55882	CROWLEY	188
TX	ARANSAS	17892	ROCKPORT	190
TX	SAN AUGUSTINE	7999	SAN AUGUSTINE	191
LA	VERNON	61961	LEESVILLE	192
TX	REFUGIO	7976	REFUGIO	202
TX	CHEROKEE	41049	RUSK	208
LA	SABINE	22646	MANY	219
LA	VERMILION	50055	ABBEVILLE	232

Table A4. Population Distribution by Distance from Port of Long Beach

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
CA	ORANGE	2410668	SANTA ANA	22
CA	LOS ANGELES	8863052	LOS ANGELES	23
CA	RIVERSIDE	1170413	RIVERSIDE	58
CA	SAN BERNARDINO	1418380	SAN BERNARDINO	68
CA	VENTURA	669016	VENTURA	82
CA	SAN DIEGO	2498016	SAN DIEGO	107
CA	SANTA BARBARA	369608	SANTA BARBARA	108
CA	KERN	543981	BAKERSFIELD	135
CA	SAN LUIS OBISPO	217162	SAN LUIS OBISPO	198
CA	TULARE	311921	VISALIA	204
CA	KINGS	101469	HANFORD	215
CA	IMPERIAL	109303	EL CENTRO	216
CA	INYO	18281	INDEPENDENCE	265

Table A5. Population Distribution by Distance from Port of Seattle

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
WA	KING	1507305	SEATTLE	1
WA	KITSAP	189731	PORT ORCHARD	23
WA	SNOHOMISH	465642	EVERETT	28
WA	PIERCE	586203	TACOMA	31
WA	JEFFERSON	20406	PORT TOWNSEND	56
WA	ISLAND	60195	COUPEVILLE	58
WA	THURSTON	161238	OLYMPIA	59
WA	SKAGIT	79545	MOUNT VERNON	60
WA	MASON	38341	SHELTON	77
WA	CLALLAM	56210	PORT ANGELES	82
WA	WHATCOM	127780	BELLINGHAM	88
WA	LEWIS	59358	CHEHALIS	88
WA	GRAYS HARBOR	64175	MONTESANO	99
WA	KITTITAS	26725	ELLENSBURG	105
WA	SAN JUAN	10035	FRIDAY HARBOR	114
WA	COWLITZ	82119	KELSO	127
WA	PACIFIC	18882	SOUTH BEND	128
WA	YAKIMA	188823	YAKIMA	138
WA	CHELAN	52250	WENATCHEE	140
OR	COLUMBIA	37557	SAINT HELENS	151
WA	WAHKIAKUM	3327	CATHLAMET	152
WA	DOUGLAS	26205	WATERVILLE	162
WA	CLARK	238053	VANCOUVER	167

Table A5. Population Distribution by Distance from Port of Seattle (Continued)

STATE	COUNTY	POPULATION	COUNTY SEAT	DISTANCE
WA	GRANT	54798	EPHRATA	172
OR	CLATSOP	33301	ASTORIA	174
OR	MULTNOMAH	583887	PORTLAND	174
WA	BENTON	112560	PROSSER	188
OR	WASHINGTON	311554	HILLSBORO	194
WA	KLICKITAT	16616	GOLDENDALE	205
WA	SKAMANIA	8289	STEVENSON	208
OR	HOOD RIVER	16903	HOOD RIVER	219
WA	OKANOGAN	33350	OKANOGAN	229
OR	TILLAMOOK	21570	TILLAMOOK	240

APPENDIX 2

```
      PROGRAM TOPORT
      DOUBLE PRECISION VOLUME,DISTANCE,CAPACITY,MPG,DISTL,
     1 SPEEDH,SPEEDL,LOAD,UNLOAD,DAYS,HOURS,MAINTE,FCOST,
     1 OPERCOST,LCOST,ADFACTOR,TKCOST,RESIDUAL,AMPERIOD,
     1 DISCOUNT,TRIP1,USE,FUEL,TRIPHOUR,MANHOUR,TKTRIP1,
     1 FUELCOST,MAINCOST,DRIVCOST,TOCOST,RESVALUE,
     1 AMFACTOR,TTKCOST,TOTCOST,UNITCOST,TKN,TRUCK1,
     1 DENSITY,COSTPMT,VOLUMEMT
      INTEGER N,K,TRUCK,TRIP,TKTRIP,WASTE
      VOLUME = 150000
      DISTANCE = 80
      CAPACITY = 30
      MPG = 4
      DISTL = 20
      SPEEDH = 35
      SPEEDL = 25
      LOAD = 30
      UNLOAD = 15
      DAYS = 360
      HOURS = 8
      MAINTE = 2
      FCOST = 1.3
      OPERCOST = 0.6
      LCOST = 16
      ADFACTOR = 1.25
      TKCOST = 112500
      RESIDUAL = 0.15
      AMPERIOD = 6
      DISCOUNT = 7.25
      WASTE = 1
      DO 100 K=5,100,5
      DISTANCE = K
*     DO 100 N=1000, 150000, 1000
*     VOLUME = N
      OPEN(12,FILE='C:\NRL\DAT.OUT',STATUS='OLD')
      TRIP1 = VOLUME/CAPACITY
      IF (TRIP1.GT.INT(TRIP1)) THEN
      TRIP = INT(TRIP1)+1
      ELSE
      TRIP = INT(TRIP1)
      END IF
      USE = 2*DISTANCE*TRIP
      FUEL = USE/MPG
      IF (DISTANCE.LE.DISTL) THEN
      TRIPHOUR = 2*(DISTANCE/SPEEDL)+LOAD/60+UNLOAD/60
      ELSE
      TRIPHOUR = 2*((DISTANCE-DISTL)/SPEEDH+DISTL/SPEEDL)+
     1          LOAD/60+UNLOAD/60
      END IF
      MANHOUR = 1.1*TRIPHOUR*TRIP
```

```
      TKTRIP1 = DAYS*(HOURS-MAINTE)/TRIPHOUR
      IF (TKTRIP1.GT.INT(TKTRIP1)) THEN
      TKTRIP = INT(TKTRIP1)+1
      ELSE
      TKTRIP = INT(TKTRIP1)
      END IF
      TRUCK1 = FLOAT(TRIP)/FLOAT(TKTRIP)
      TKN = TRUCK1 -INT(TRUCK1)
      IF (TKN.GT.0) THEN
      TRUCK = INT(TRUCK1)+1
      ELSE
      TRUCK = INT(TRUCK1)
      END IF
      FUELCOST = FUEL*FCOST
      MAINCOST = USE*OPERCOST
      DRIVCOST = MANHOUR*LCOST
      TOCOST = ADFACTOR*(FUELCOST+MAINCOST+DRIVCOST)
      RESVALUE = RESIDUAL*TKCOST
      AMFACTOR = 0.01*DISCOUNT/(1-1/(1+0.01*DISCOUNT)**AMPERIOD)
      TTKCOST = FLOAT(TRUCK)*((TKCOST-RESVALUE)*AMFACTOR+
     1          0.01*RESVALUE*DISCOUNT)
      TOTCOST = TOCOST + TTKCOST
      UNITCOST = TOTCOST/VOLUME
      IF (WASTE.EQ.1) THEN
      DENSITY = 64.38
      ELSE
      DENSITY = 127.5
      END IF
      VOLUMEMT = VOLUME*27*DENSITY*0.454/1000
      COSTPMT = TOTCOST/VOLUMEMT
*      WRITE(12,10) VOLUME, DISTANCE, TOTCOST, TRUCK
*   10 FORMAT(2X, 'VOLUME=', F10.1, 2X,
*     1         'DISTANCE=',F10.1,2X,'TOTCOST=',
      1         F10.2,2X,'TRUCK=',I3)
      WRITE(12,20) VOLUMEMT, COSTPMT, UNITCOST, TKTRIP
   20 FORMAT(2X, 'VOLUMEMT=', F10.1, 2X,
     1         'COSTPMT=',F10.2,2X,'UNITCOST=',
     1         F10.2,2X,'TKTRIP=',I5)
  100 CONTINUE
      STOP
      END
```

APPENDIX 3

```
      PROGRAM TOSITE
      DOUBLE PRECISION VOLUMEP,DISTP,CAPV,SPEED,LOADV,
     1 UNLOADV,DAYS,HOURS,VFCOST,VLCOST,CREW,PERSON,
     1 VMLCOST,VPLCOST,CONSUMCT,MCOST,APFACTOR,VCOST,
     1 AMPERIOD,DISCOUNT,TRIPP1,USEV,TRIPHV,VTRIP1,
     1 FUELCV,LUBECV,MANHOURV,MANHOURP,CREWCOST,
     1 PORTLC,CONSUMC,VTOCOST,AMFACTOR,TVCOST,TOTPCOST,
     1 UPCOST,VN,VESSEL1,TOTPC,DOWNTIME,VOLP,ACFACTOR
      INTEGER N,K,VESSEL,TRIPP,VTRIP,PORT,SITE,TECH,
     1 WASTEVOL
      PORT = 1
      SITE = 1
      TECH = 1
      WASTEVOL = 1
      DO 100 PORT = 1,5,1
      DO 100 SITE = 1,5,1
      DO 100 TECH = 1,4,1
      IF (PORT.EQ.1.AND.SITE.EQ.3) GOTO 100
      IF (PORT.EQ.1.AND.SITE.EQ.4) GOTO 100
      IF (PORT.EQ.1.AND.SITE.EQ.5) GOTO 100
      IF (PORT.EQ.2.AND.SITE.EQ.3) GOTO 100
      IF (PORT.EQ.2.AND.SITE.EQ.4) GOTO 100
      IF (PORT.EQ.2.AND.SITE.EQ.5) GOTO 100
      IF (PORT.EQ.3.AND.SITE.EQ.1) GOTO 100
      IF (PORT.EQ.3.AND.SITE.EQ.2) GOTO 100
      IF (PORT.EQ.3.AND.SITE.EQ.4) GOTO 100
      IF (PORT.EQ.3.AND.SITE.EQ.5) GOTO 100
      IF (PORT.EQ.4.AND.SITE.EQ.1) GOTO 100
      IF (PORT.EQ.4.AND.SITE.EQ.2) GOTO 100
      IF (PORT.EQ.4.AND.SITE.EQ.3) GOTO 100
      IF (PORT.EQ.5.AND.SITE.EQ.1) GOTO 100
      IF (PORT.EQ.5.AND.SITE.EQ.2) GOTO 100
      IF (PORT.EQ.5.AND.SITE.EQ.3) GOTO 100
      IF (WASTEVOL.EQ.1) THEN
      IF (PORT.EQ.1) VOLUMEP = 2841000
      IF (PORT.EQ.2) VOLUMEP = 1095000
      IF (PORT.EQ.3) VOLUMEP = 336000
      IF (PORT.EQ.4) VOLUMEP = 1511000
      IF (PORT.EQ.5) VOLUMEP = 409000
      ELSE IF (WASTEVOL.EQ.2) THEN
      IF (PORT.EQ.1) VOLUMEP = 1835000
      IF (PORT.EQ.2) VOLUMEP = 537000
      IF (PORT.EQ.3) VOLUMEP = 336000
      IF (PORT.EQ.4) VOLUMEP = 1341000
      IF (PORT.EQ.5) VOLUMEP = 318000
      ELSE IF (WASTEVOL.EQ.3) THEN
      IF (PORT.EQ.1) VOLUMEP = 4815000
      IF (PORT.EQ.2) VOLUMEP = 1225000
      IF (PORT.EQ.3) VOLUMEP = 445000
      IF (PORT.EQ.4) VOLUMEP = 1954000
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IF (PORT.EQ.5) VOLUMEP = 492000
ELSE
IF (PORT.EQ.1) VOLUMEP = 3031000
IF (PORT.EQ.2) VOLUMEP = 599000
IF (PORT.EQ.3) VOLUMEP = 445000
IF (PORT.EQ.4) VOLUMEP = 1784000
IF (PORT.EQ.5) VOLUMEP = 390000
END IF
IF (PORT.EQ.1.AND.SITE.EQ.1) DISTP = 787.3
IF (PORT.EQ.1.AND.SITE.EQ.2) DISTP = 1044.7
IF (PORT.EQ.2.AND.SITE.EQ.1) DISTP = 560.6
IF (PORT.EQ.2.AND.SITE.EQ.2) DISTP = 1032.5
IF (PORT.EQ.3.AND.SITE.EQ.3) DISTP = 267.2
IF (PORT.EQ.4.AND.SITE.EQ.4) DISTP = 286.6
IF (PORT.EQ.4.AND.SITE.EQ.5) DISTP = 782.1
IF (PORT.EQ.5.AND.SITE.EQ.4) DISTP = 851.2
IF (PORT.EQ.5.AND.SITE.EQ.5) DISTP = 920.2
CAPV = 25000
SPEED = 15
LOADV = 5.2
IF (TECH.EQ.1) UNLOADV = 2
IF (TECH.EQ.2) UNLOADV = 6
IF (TECH.EQ.3) UNLOADV = 10
IF (TECH.EQ.4) UNLOADV = 12
IF (SITE.EQ.1) DAYS = 325
IF (SITE.EQ.2) DAYS = 307
IF (SITE.EQ.3) DAYS = 329
IF (SITE.EQ.4) DAYS = 266
IF (SITE.EQ.5) DAYS = 248
DOWNTIME = 8
HOURS = 24
VFCOST = 40
VLCOST = 0.5
CREW = 9
PERSON = 6
VMLCOST = 55
VPLCOST = 45
IF (TECH.EQ.1) CONSUMCT = 72033
IF (TECH.EQ.2) CONSUMCT = 89992
IF (TECH.EQ.3) CONSUMCT = 142090
IF (TECH.EQ.4) CONSUMCT = 2700
IF (TECH.EQ.1) MCOST = 2.32E6
IF (TECH.EQ.2) MCOST = 3.47E6
IF (TECH.EQ.3) MCOST = 3.92E6
IF (TECH.EQ.4) MCOST = 4.64E6
APFACTOR = 1.20
IF (TECH.EQ.1) VCOST = 94.83E6
IF (TECH.EQ.2) VCOST = 136.30E6
IF (TECH.EQ.3) VCOST = 154.87E6
IF (TECH.EQ.4) VCOST = 141.83E6
ACFACTOR = 1
```

```
      AMPERIOD = 8
      DISCOUNT = 7.25
*      DO 100 K=100,1500,100
*      DISTP = K
*     DO 100 N=100000, 6000000, 100000
*     VOLUMEP = N
      OPEN(12,FILE='C:\NRL\DAT.OUT',STATUS='OLD')
      TRIPP1 = VOLUMEP/CAPV
      IF (TRIPP1.GT.INT(TRIPP1)) THEN
      TRIPP = INT(TRIPP1)+1
      ELSE
      TRIPP = INT(TRIPP1)
      END IF
      USEV = 2*DISTP*TRIPP
      TRIPHV = 2*(DISTP/SPEED)+LOADV+UNLOADV+DOWNTIME
      VTRIP1 = DAYS*HOURS/TRIPHV
      IF (VTRIP1.GT.INT(VTRIP1)) THEN
      VTRIP = INT(VTRIP1)+1
      ELSE
      VTRIP = INT(VTRIP1)
      END IF
      VESSEL1 = FLOAT(TRIPP)/FLOAT(VTRIP)
      VN = VESSEL1 -INT(VESSEL1)
      IF (VN.GT.0) THEN
      VESSEL = INT(VESSEL1)+1
      ELSE
      VESSEL = INT(VESSEL1)
      END IF
      FUELCV = USEV*VFCOST
      LUBECV = USEV*VLCOST
      MANHOURV = 1.1*CREW*TRIPHV*TRIPP
      MANHOURP = 1.1*365*24*PERSON*VESSEL
      CREWCOST = MANHOURV*VMLCOST
      PORTLC = MANHOURP*VPLCOST
      CONSUMC = TRIPP*CONSUMCT
      VTOCOST = APFACTOR*(FUELCV+LUBECV+CREWCOST+PORTLC+
     1           CONSUMC+MCOST*FLOAT(VESSEL))
      AMFACTOR = 0.01*DISCOUNT/(1-1/(1+0.01*DISCOUNT)**AMPERIOD)
      TVCOST = FLOAT(VESSEL)*VCOST*AMFACTOR*ACFACTOR
      TOTPCOST = VTOCOST + TVCOST
      TOTPC = TOTPCOST/1000000
      UPCOST = TOTPCOST/VOLUMEP
      VOLP = VOLUMEP/1000000
*      WRITE(12,10) PORT,SITE,TECH
*   10 FORMAT(2X,'PORT=',I3,2X,'SITE=',I3,2X,'TECH=',I3)
*      WRITE(12,20) VOLUMEP,DISTP,TOTPC,VESSEL,UPCOST,VTRIP
*  20 FORMAT(2X,'VOLUMEP=',F10.0,2X,'DISTP=',F6.0,2X,'TOTPCOST=',
*     1    F6.2,2X,'VESSEL=',I3,2X,'UPCOST=',F6.2,2X,'VTRIP=',I4)
      WRITE(12,30) PORT,SITE,TECH,VOLP,DISTP,VTRIP,VESSEL,
     1             TOTPC, UPCOST
   30 FORMAT(I1,2X,I1,2X,I1,2X,F4.1,2X,F6.0,2X,
```

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   1         I4,2X,I3,2X,F6.2,2X,F6.2)
100 CONTINUE
    STOP
    END
```

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